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MAGMATIC ORE DEPOSITS, SUDBURY, ONT.

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INTRODUCTION.

No other types of deposit have perhaps excited more scientific interest than those for which a syngenetic magmatic origin has been claimed. This is especially true for deposits of sulphides

supposed to be of magmatic origin. Geologists have had little difficulty in accepting a magmatic origin for deposits in which the ore minerals are also common rock-forming minerals, such as the iron ore deposits. On the other hand, there has been hesitancy in accepting a like origin for deposits in which the ore minerals are not common accessory minerals of rocks, such as sulphides. For this reason the Sudbury deposits have attracted more than usual interest,—an interest increased by the fact that these ore bodies constitute the greatest nickel deposits in the world, and because both a magmatic and hydrothermal origin have been claimed for them. Considerable controversial literature has appeared upon the subject, and recent contributions indicate that the subject of origin will be reopened with renewed vigor.

For those geologists whose field experience of the Sudbury ores is limited or lacking, the more or less opposing array of published facts and conclusions offer difficulty for a clear understanding of the origin of these deposits and of magmatic sulphide deposits in general. The writer finds himself in this class of geologists, and in an attempt to clarify his mind upon the subject investigated the literature pertaining to the deposits and studied Sudbury rocks and ores by means of thin sections and polished specimens. In this investigation were encountered certain conclusions supported by convincing evidence, and also opposing conclusions supported by equally convincing evidence. Where the supporting evidence for both sides is strong, it is rather suggestive that a more correct conclusion would be one which includes some of the evidence presented by each side. Such a conclusion has been presented by one investigator.[1]

A modification of this conclusion is presented by the writer, and it is believed that it is supported by convincing evidence on both sides and meets some of the objections advanced by different investigators.

[1] Ernest Howe, "Petrographical Notes on the Sudbury District," ECON. GEOL., Vol. XI., p. 503, 1914.

FIELD RELATIONS.

ROCK FORMATIONS.

Since a knowledge of the field relations of the Sudbury region is indispensable for an understanding of what is to follow, a brief summary from the writings of those who have worked most in the field is presented.[2]

The formations of the Sudbury region correspond to a great spoon with its point to the southwest. Its length is about thirty-six miles and width about fifteen miles. The center of the spoon is occupied by 9,000 feet of sandstones, shales, and conglomerates of upper Huronian age. The rim of the spoon, varying width from one to four miles, is what Coleman has termed the "Nickel Eruptive."[3] This is an intrusive mass consisting of norite in its outer margin and grading into micropegmatite in its inner and upper margin. It is with the "nickel eruptive" that the ore bodies are more or less directly associated.

The spoon rests on a great thickness of pre-Cambrian rocks made up of a crystalline group,—largely eruptive,—of Keewatin, Grenville, and Laurentian age, and a series of sedimentary rocks chiefly quartzites, which Coleman has termed the Sudbury series.[4] Their thickness is estimated to be 30,000 feet. Included within the Sudbury series are many basic eruptives consisting of gabbro, norite, and greenstones made from basic eruptives. Coleman[5] also includes in this series acid eruptives of coarse granite-syenite and granitoid gneiss which lie directly under part of the rim of norite-micropegmatite on the south side of the spoon and form a foot wall to the norite and some of the ore bodies. The northern half of the spoon and the southeastern edge of the Lower

[2] Barlow, A. E., Geol. Surv. Can., Ann. Rep., Vol. 14, part H, 1901.
Coleman, A. P., "The Nickel Industry," Can. Dept. of Mines, Mines Branch, No. 170, 1913.
Knight, C. W., "Origin of the Sudbury Nickel Copper Deposits," *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.
See also geologic maps accompanying Coleman's report.

[3] "The Sudbury Laccolithic Sheet," *Jour. Geol.*, Vol. 15, p. 252, 1907.

[4] "The Nickel Industry," Can. Dept. of Mines, Mines Branch, No. 170, p. 6, 1913.

[5] *Op. cit.*, p. 8.

Huronian are underlain by granite gneiss and hornblende schist of Laurentian age, much older than the nickel eruptive.

STRUCTURAL RELATIONS OF ROCKS.

The sedimentary and included eruptive rocks of the Sudbury region are concluded by Barlow and Coleman to belong to the pre-Cambrian. Coleman[6] classifies the older greenstones and green schists as Keewatin; the coarse white quartzites and fine grained gray gneiss as Grenville; the Sudbury series as probably earlier than Lower Huronian; the graywacke and conglomerate as Lower Middle Huronian; and the sandstones, slates, tuffs, and conglomerates within the spoon as Upper Huronian. The granitic rocks at the southeast edge of the Sudbury series and those surrounding the northern half of the spoon are considered by him[7] to be Laurentian and intrusive into the Sudbury but far older than the sediments and the nickel eruptive.

Included with the Laurentian granitic rocks is the granite area in the vicinity of the Creighton mine upon which the nickel eruptive is presumed to have rested. Coleman[8] considers the small area of granite between the Murray and Little Stobie mines to be later than the nickel eruptive and regards the eruptives within the Sudbury series as being in part older and part younger than the nickel eruptive.

The nickel eruptive is intrusive into all of the sedimentary rocks and is regarded by Coleman as later in age than the granitic rocks which form its footwall on the northern and a part of the southern sides.

Knight[9] has more recently shown that the granite footwall of the norite on the south side of the spoon is not older than the norite but is intrusive into it.

Coleman[10] believes that the nickel eruptive was intruded in the

[6] *Op. cit.*, p. 5.
[7] *Op. cit.*, p. 8.
[8] *Idem*, p. 8.
[9] "Origin of the Sudbury Nickel-copper Deposits," *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.
[10] *Idem*. p. 10.

form of a great sill between the ancient surface of the older rocks and the basal conglomerate of the overlying Huronian series which now occupies the center of the spoon. After the nickel eruptive reached its resting place it is proved to have undergone differentiation in situ resulting in its lower outer edge in a norite which grades insensibly into micropegmatite in its upper inner edge. Field relations show that there are roughly 3 parts acid rock to 2 parts basic rock.[11]

Later than the nickel eruptive and representing the latest phase of igneous rock processes in the region are numerous large diabase dikes which cut the norite and ore bodies[12] and are themselves cut by small granite dikes.

ORE DEPOSITS.[13]

The ore deposits at Sudbury have long been worked for their nickel and copper content. In addition platinum and small amounts of silver, gold, and palladium are won from the ores, and irridium and osmium have also been noted. The gangue is the enclosing rocks.

The Sudbury district is the source of the world's greatest nickel supply and is also an important producer of copper. The present ore reserves indicate a supply for many years to come, and development and exploratory work is continually exposing more ore bodies. Geologic conditions indicate that future work will add greatly to the present reserves so that a long life may be expected for the district.

Character of Ore Bodies.—Some of the important features in any consideration of the origin of the Sudbury ore deposits are the shapes of the ore bodies, their position with respect to the norite, the nature of the contacts between the ore and norite, and the relation of the metallic minerals to each other and to the en-

[11] Coleman, A. P., *Jour. of Geol.*, Vol. 15, p. 772, 1907.

[12] Coleman, A. P., *op. cit.*, p. 11.

[13] For the best description of the ore deposits the reader is referred to Coleman, A. P., "The Nickel Industry," Mines Branch, No. 170, 1913, from which the description of the ore bodies given here is largely drawn.

closing rock minerals. It is necessary therefore that these features be reviewed.

Coleman[14] distinguishes two main varieties of ore bodies, "marginal" and "offset," which he summarizes as follows:

> Marginal (*a*) dipping toward the axis of the basin, ores with comparatively little rock and more than twice as much nickel as copper.
>
> (*b*) Faulted marginal—irregular in shape and character—usually mixed with much rock and carrying as much copper as nickel, or sometimes more.
>
> Offsets: (*a*) Columnar offsets, roughly cylindrical bodies nearly vertical and going to great depths. Ore usually rich in copper and the precious metals.
>
> (*b*) Parallel offsets—not columnar, but sheet-like, dipping inward toward the basic edge. Ore like that of the usual marginal deposits.

Marginal Deposits.—The marginal deposits are one of the striking features of the Sudbury district. They occur at the basic margin of the norite, so that the norite forms the hanging wall and the adjoining country rock the footwall. They all dip toward the center of the basin at an average of 30°–35°. Their thickness varies from a few to a hundred feet or more and their length up to 700 feet. Their depth is as yet unknown. The Creighton ore body, which is the most important of this type of deposit, has been found to extend to a depth of at least 900 feet.[15] Coleman states[16] that the ore bodies may have a distinct footwall or may penetrate it along fissures and enclose blocks of it. He considers the hanging wall to merge gradually into a blending of rock and ore called pyrrhotite-norite, and then into pure norite with blebs of ore.

Howe's description of the Creighton differs from that of Coleman's in that he considers the change from ore to norite to be less gradual and the

> graduation to be due to a mechanical mixture of sulphides and norite in the transition zone, and not to a graduation in a mineralogical sense.

[14] Coleman, A. P., Can. Dept. Mines., Mines Branch, No. 170, pp. 34 and 38, 1913.

[15] Coleman, *op. cit.*, p. 34.

[16] *Idem*, p. 34.

In all places where transition from ore to rock is supposed to exist, the norite has been extensively shattered in the neighborhood of the ore, and the sulphides appear to have penetrated the norite along the cracks and fissures so formed, while angular fragments of norite are included in the sulphides close to the rock. The veinlets of sulphides die out gradually in the norite away from the massive ore, while the rock fragments included in the sulphides become numerous and smaller in size as their distance from the hanging wall increases. There is thus a transition from ore to rock in a mechanical sense, and from a mining standpoint the expression is justifiable. Neither megascopically nor with the aid of the microscope could the writer recognize a petrographical graduation.[17]

Faulted Marginal Deposits.—Coleman[18] cites the Cream Hill and Garson mines as examples of the faulted marginal deposits. He considers these to have been formed, or begun, as the usual marginal type, "but later faults have crushed and split up the country rock and the ore wandered into the fissures between the blocks, either at the time as molten sulphides, or later through water transport." The ores are richer in copper and contain much quartz, carbonates, sphalerite, and galena "as a result of circulating waters."

Offset deposits.—The offset deposits, as defined by Coleman,[19] are dike-like masses of ore and rock that extend outward from the main norite mass into the underlying older rocks, or more or less separate bodies having no visible connection with the main norite body. The columnar offsets as at Copper Cliff and Victoria mines are pipe-like bodies, somewhat resembling the Kimberley diamond pipes, from 50 to 200 feet in diameter. In the Victoria mine have been developed to a depth of 1,400 feet. Coleman[20] states in regard to these deposits,

The contents of these pipe-line bodies differs considerably from those of marginal deposits, being more rocky, as might be expected, and containing usually more copper ore, as well as more of the precious metals, gold, silver, platinum and palladium. . . . There is usually more evidence of water action than in the marginal mines. . . .

[17] Howe, Ernest, ECON. GEOL., Vol. 9, p. 514, 1914.
[18] *Op. cit.*, p. 35.
[19] *Idem*, p. 35.
[20] *Idem*, p. 37.

The parallel offset deposits are long irregular sheets of norite and ore, roughly parallel and dipping toward the main norite sheet. They are separated from the norite by other rocks and have no visible connection with it. The Frood and Stobie mines are examples of this type.

MINERALS.

Of the minerals that compose the Sudbury ores pyrrhotite, chalcopyrite, and pentlandite are the most important. Of these pyrrhotite is abundant, chalcopyrite is common, and pentlandite, though scattered through all the ores, is rarely seen with the naked eye. Other minerals that occur in the district are pyrite, marcasite, polydymite, willemite, niccolite, gersdorffite, magnetite, titaniferous magnetite, cassiterite, galena, zincblende, molybdenite, and sperrylite. In addition, the usual oxidized compounds of some of these minerals are to be found.

The pyrrhotite is widely scattered throughout the norite of the district and makes up the greater part of the ore bodies. Intimately admixed with it are chalcopyrite and pentlandite. The chalcopyrite may readily be distinguished in the ore, and bunches of pentlandite may occasionally be discerned, although it is usually revealed only by means of the microscope. All of the other minerals are more or less rare. The pyrite, galena, and zincblende are usually associated with quartz and carbonate and commonly occur in veins which, according to Coleman,[21] are later than the main ore bodies. They occur in the offset deposits more than in the marginal ore bodies.

PREVIOUS VIEWS OF THE ORIGIN OF THE SUDBURY ORES.

The scientific interest attached to the celebrated Sudbury deposits is due not only to their unique character but to the problem of origin they present. Because of their complexity the literature concerning them is voluminous. The previous investigators may be divided broadly into two schools; those favoring an origin by means of hydrothermal agencies, and those by mag-

[21] *Op. cit.*, p. 27.

matic differentiation. Some modifications of both hypotheses have been advanced. It is intended here to mention the views pertaining to the origin of the Sudbury deposits, to outline briefly the more recent theories and then to discuss them separately.

The earlier views have been so excellently summarized by A. E. Barlow[22] that it is necessary only to refer to them without further discussion. Barlow[23] states that the first investigators, Collins, Merritt, and Bell, ascribed a hydrothermal origin to these deposits: the same origin was adopted later by Emmons, Bush, Argall, and others.

The first to advocate an igneous origin for the Sudbury deposits was Barlow, and somewhat later Vogt advanced a similar origin to explain the Norwegian deposits. Since that time Barlow's views have been advocated by Adams, Browne, Kemp, Walker, and others. In later years Coleman has carried on extensive work in the Sudbury district and is perhaps the strongest advocate of the views of Barlow. When Barlow's explanation of the origin of the Sudbury ores appeared it was widely accepted, and no dissenting opinion appeared in the literature until 1903 when C. W. Dickson[24] attacked the igneous origin. From a study chiefly by means of the microscope he coucluded that the sulphides were deposited from solution. A similar study led Beck[25] to the same conclusios. Later Campbell and Knight[26] investigated the problem by a metallographic study and supported Dickson's views.

In 1911 Ernest Howe and J. D. Irving visited the Sudbury region, the former making a second trip in 1913. Some of Howe's observations, with which Irving is in agreement, were published in an article[27] in which he advocated a modified igneous origin for the Sudbury deposits. In 1916 a preliminary article appeared

[22] ECON. GEOL., Vol. 1, p. 454, 1906.

[23] *Idem*, p. 459.

[24] "The Ore Deposits of Sudbury, Ont.," *T. A. I. M. E.*, Vol. 34, pp. 1–65, 1903.

[25] "Nature of Ore Deposits," p. 41, 1903.

[26] "Microstructure of Nickelliferous Pyrrhotites," ECON. GEOL., Vol. 2, p. 350, 1907.

[27] ECON. GEOL., Vol. IX., p. 503, 1914.

by C. W. Knight[28] in which, as a result of extensive field work, he shows that the age relations of some of the intrusive rocks are different from what had hitherto been considered, and he concludes the ores are of hydrothermal origin. The latest publication dealing with the Sudbury deposits is that by Tolman and Rogers[29] in which the ores are believed to have been formed by replacement of the norite by the action of "mineralizers."

OUTLINE OF RECENT VIEWS OF ORIGIN OF SUDBURY ORES.

From the outline above it may be seen that the views of the origin of the Sudbury ores are conflicting.

Dickson based his ideas of a hydrothermal origin chiefly on the microscopic relations of the ore and rock minerals. He obtained specimens from a large number of the mines, all of which showed a brecciated character both on a large scale and microscopic, in which the ore "prevailingly occurs as a cement for brecciated rock fragments and along shear planes."[30] He found that these included rock fragments were free from ore except in veinlets cutting across them, and in general that the sulphides were most abundant where the enclosing rock was most crushed. Thus, his conclusion is that the shearing and brecciation took place previous to the formation of the ore bodies proper.

Microscopic work led him to conclude that the sulphides had replaced the rock minerals, particularly pyroxene and hornblende, and that in some cases, as at the Mount Nickel mine, pseudomorphs of sulphides after hornblende occurred. The microscope also showed that metamorphic changes and development of secondary hornblende are most marked near the ore bodies and diminish away from them, and that the more complete the alteration of the rock the more complete has been its replacement by sulphides. He found that the sulphides tend to occur in connection with the fibrous minerals, and along planes of weakness. Practically all of his microscopic work suggested

[28] *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

[29] "Magmatic Sulphide Ores," Leland Stanford University Publications, 1916.

[30] Dickson, C. W., *op. cit.*, p. 59.

that the sulphides are decidedly later than the rock minerals, but he found a very subordinate amount of pyrrhotite which he took to be an original constituent of the rock. He also concluded that the magnetite holds a different relation to the rock minerals than to the sulphides, always being in more or less rounded grains in dark rock minerals and generally primary.

Dickson points out that the chalcopyrite occurs usually in fairly pure masses and is concentrated near the outside of the ore bodies toward the footwall. This purity and concentration are considered to be due to later mineralization by chalcopyrite which entered along fractures in ore and rock. Greater copper concentration as in the Copper Cliff mine may have been due to greater fracturing and more active solutions. Dickson's description of the Creighton mine indicates a considerable amount of brecciation with numerous angular fragments of norite surrounded by ore, and notable replacement of rock by sulphides. There also, a partial replacement of an acid rock that intrudes the norite is noted.

Later Campbell and Knight supported the findings of Dickson. Their work[31] consisted of a metallographic examination of polished specimens of ores from Sudbury, Norway, and other nickelliferous-pyrrhotite localities. By this means they found that the same relations held between the minerals in all the localities studied, that magnetite was the first mineral to form, the rock silicates next, followed by pyrrhotite, pentlandite, and chalcopyrite; the rock silicates were in general fractured, the corners rounded off and the sulphides had in part replaced the slicates. They concluded that these features were the result of deposition from ore bearing solutions.

Coleman in his article[32] on the Sudbury district which appeared later strongly advocates the igneous origin of these deposits. He asserts that Dickson was unfortunate in his choice of specimens, since he selected them chiefly from offset deposits and brecciated ore bodies, and that he did not study the other phase in which

[31] "Microstructure of Nickelliferous Pyrrhotite," ECON. GEOL., Vol. 2, p. 350, 1902.

[32] Rept. Bur. of Mines, Ont., Vol. 14, Part III., p. 17, 1905.

particles of ore in norite point more clearly to an igneous origin. In his opinion the studies of Campbell and Knight show simply the final deposition of the minerals and affirm only that a certain amount of fracturing of pyrrhotite allowed pentlandite and pyrrhotite to migrate into the fractures,[33] and he thinks[34]

that these features shown by Dickson and Campbell and Knight may be explained by a later rearrangement in which some of the minerals were dissolved and redeposited along fractures by means of circulating solutions. This rearrangement is more marked in offset deposits than in marginal ones.

Coleman's summary of the arguments in favor of an origin of the Sudbury ores by magmatic segregation are quoted.[35]

1. The ores are everywhere associated with the norite of a single eruptive sheet. No ore occurs without norite. No long stretch of the lower edge of the norite or its dike-like offsets is entirely devoid of ore.

2. Norite and ore are mixed in every degree from rock enclosing scattered particles of ore, to pyrrhotite-norite in which ore and rock are in equal amounts, and finally to almost pure ore with a few rock-forming minerals scattered through it. This relationship is found at every mine. Norite spotted with ore is sometimes found in bands a long distance from the nearest ore body and separated from the basic edge by rock free from ore.

3. The adjoining rock, granite, gneiss, greenstone, or graywacke, is never spotted with ore, and separated bodies of ore are never enclosed in it, but veinlets of ore may penetrate the country rock, and almost always blocks of it are enclosed in the ore. The shattering and crushing of the country rock took place when the nickel-eruptive forced its way between the upper sediments and the lower crytalline rocks, and the heavier and probably more fluid sulphides filled all the spaces thus opened. There are often clean walls of country rock against large bodies of pure ore.

4. The freshest norite is generally close to the ore bodies and is often shotted with ore. The best preserved hypersthenes at the Murray, Creighton, and Gertrude mines are in sections containing sulphides and not in specimens free from sulphides at a distance from the mines. No considerable amount of re-arrangement caused by water could have taken place without changing so susceptible a mineral as hypersthene into secondary minerals.

[33] Can. Dept. of Mines, Mines Branch, No. 170, p. 30, 1913.
[34] Rept. Bur. of Mines, Ont., Vol. 14, Part III., p. 19, 1905.
[35] *Op. cit.*, p. 18.

5. The marginal ore bodies show hardly a trace of hydrothermal or pneumatolytic action. There are seldom any of the minerals usual in deposits formed by water except very small quantities of quartz and calcite, and these are often in seams cutting the ore and evidently of later formation. There is no banding such as one finds where cavities are filled with minerals deposited from solution; nor are there concentric structures about the rock fragments enclosed in the ore.

6. The deposits are extremely uniform as shown by Dr. Barlow, a fact hard to account for in mines scattered along a length of 35 miles with entirely different country rocks on one side unless they have had a single source, the norite, which is as monotonous as the ores themselves.

7. The largest ore bodies are where bays of the norite project into the country rock or on offsets from such funnel-like bays; there is seldom a deposit of importance along a straight margin; and no ores are found on parts of the margin which project inwards instead of outwards. This is intelligible if the ore settles into the hollows under the molten sheet, but quite unaccountable if it was brought in solution from elsewhere along the channels furnished by the contact.

From field and microscopic evidence Howe[36] found nothing to suggest that the ore bodies had been formed by replacement of the norite, nor did microscopic evidence indicate a gradation from norite to massive sulphide in a petrographic sense. He also notes the brecciated character of the Creighton ore body and states that veinlets of sulphides penetrate the norite hanging wall and norite fragments included in the ore.

As a result of these investigations Howe[37] proposes a modification of the magmatic theory. He suggests

that the molten sulphides were originally introduced into their present position in a molten condition. The brecciated character of the contacts between ore and country rock, as well as the fineness of the grain of the norite close to the contact would seem to indicate that the sulphides were intruded after the norite had cooled and that they represent, perhaps, an end product in the differentiation of the magma from which the norite was derived. In other words, the differentiation, of sulphides and silicates at least, was affected in the magmatic reservoir and not in the laccolithic chamber. This modified hypothesis in Howe's opinion would relieve the theory of magmatic origin of the burden of many troublesome problems in physics and chemistry.

[36] ECON. GEOL., Vol. 9, p. 503, 1914.
[37] *Idem*, p. 521.

Again in Knight's[38] latest contribution to the subject we find a further advocating of the hydrothermal origin of the deposits. As a result of recent field work he has found that the granite footwall of the Creighton ore body upon which, according to the magmatic theory, the molten sulphides are supposed to have settled out of the magma, is not older than the norite as has been assumed, but is younger. He says:[39]

> Clearly then, since the granite is younger than the norite, the molten sulphides could not have settled to the bottom of the norite magma and rested on the granite footwall, for the very good reason that the granite was not there when the norite was erupted.

He also states at the Frood or No. 3 mine the ore is not wholly in norite, as has been supposed, but occupies a crushed zone in schistose beds of graywacke and to be a less extent in norite. Some of the sulphides also impregnate the basic intrusives. The brecciated character of the Worthington mine is pointed out, and it is emphasized that sulphides are spotted in granite, greenstone, and graywacke in a similar manner to the spotting of norite so much emphasized by Coleman as an indication of magmatic origin. From these and other data to be dealt with in a forthcoming paper, Knight concludes the deposits to be of hydrothermal origin.

The latest publication dealing with the Sudbury ores is that by Tolman and Rogers.[40] From microscopic work with thin sections and polished specimens they conclude that the sulphides are all later than the rock minerals and that they have been formed by a replacement of the silicates, and that in general the later formed ore minerals replace the earlier ore minerals. In addition to replacement in all degrees of completeness they record veinlets of sulphide cutting across the rock silicates. They also find that the order of formation of the minerals is silicates, magnetite and ilmenite, pyrrhotite, pentlandite, chalcopyrite. An absence of hydrothermal and pneumatolytic alteration of the

[38] *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

[39] *Idem*, p. 812.

[40] "Magmatic Sulphide Ores," Tolman, C. F., Jr., and Rogers, A. F., Leland Stanford Jr. Univ. Publications, 1916.

rocks accompanying the metallization is noted but such alteration has occurred to a limited extent after the formation of the sulphides.

Tolman and Rogers disagree with Dickson "as to the hydrothermal 'secondary aequous' origin of the ores" but agree "with the supporters of the magmatic hypothesis that the ores were formed within the magmatic period. They were, however, not formed at an early stage and not by the sinking of the sulphide constituents."

Their conception is that the ores were formed at a late magmatic stage by the action of "mineralizers," and that the sulphides replace the silicates. While they apply the term "magmatic" to these deposits, they do not imply the usual significance of the term, and while they consider them to have been formed by replacement as a result of "mineralizers" or "mineralizing solutions," they differentiate from the usual replacement in that no hydrothermal alteration took place at the time the ores were deposited.

DISCUSSION OF RECENT VIEWS.

From the above summary of some of the recent views regarding the origin of the Sudbury ores, it will be seen that they are conflicting and there is much that is plausible and convincing on each side, while no one theory adequately explains all of the evidence that has been produced. It would appear also that no one view can be completely discarded. Some of the points for and against each hypothesis will therefore be discussed.

MAGMATIC SEGREGATION.

The hypothesis of magmatic segregation has in its favor the close association between ore and norite. As pointed out by Coleman practically all of the ore bodies are in or immediately adjacent to norite, and no part of the main norite mass or its dike-like offsets is entirely devoid of ore. While this same association is true to some extent of deposits clearly not of magmatic origin, as the disseminated copper ores in porphyry intrusions such as

at Bingham, Utah, where some sulphides are scattered through practically all of the monzonite porphyry, it is nevertheless a strongly suggestive argument. Another suggestive argument in favor of magmatic segregation is the more or less world wide association of norite and nickeliferous pyrrhotite, in which the sulphides are invariably at or near the border of the norite. As far as is known there is no conclusive evidence against sulphides, such as occur at Sudbury, forming a part of an igneous rock and occurring in a molten condition. On the contrary many investigators have produced evidence from widely scattered localities showing that sulphides do occur originally in igneous rocks. Also David Browne has shown that in a pot of matte the nickel tends to concentrate toward the center and the copper toward the margins, simulating the conditions of occurrence of the Sudbury ores.[41]

That the nickel eruptive itself has undergone a differentiation from norite to micropegmatite is disputed by none. The argument of further differentiation of sulphides from norite is therefore reasonable and suggestive though by no means conclusive.

One of the most noticeable features in connection with all ore bodies formed by hydrothermal processes is the pronounced alteration which the containing rock has undergone. This is especially true of deposits where the sulphides are more or less scattered through the rock as is the case in the Sudbury deposits. As Coleman points out "no considerable amount of rearrangement caused by water could have taken place without changing so susceptible a mineral as hypersthene into secondary minerals."[42] Therefore the paucity of a pronounced and intense alteration of all the norite surrounding the ore at Sudbury is an argument against the hydrothermal origin of those ores and may be construed as an argument in favor of magmatic segregation, though it cannot be used exclusively in favor of such an origin.

The scarcity of such ore minerals in most of the Sudbury mines as are commonly indicative of deposits of hydrothermal origin is a further indication that these deposits are not to be classed as

[41] *Columbia Univ. School of Mines Quarterly*, p. 279, 1895.
[42] Coleman, A. P., Rept. Bur. Mines, Ont., Vol. 14, p. 18, 1905.

entirely of hydrothermal origin. This argument in conjunction with other criteria might be suggestive for a magmatic segregation origin, though again it cannot be considered as a conclusive proof in favor of it.

The lack of banding and concentric and preserved structures, such as characterize ores deposited in open cavities or by replacement, and the lack of drusy filled cavities, is suggestive of an origin other than hydrothermal, but cannot necessarily be used as a proof of magmatic segregation, as has been done by Coleman and others, any more than it could be used as a proof of contact metamorphic deposits.

One of the strongest arguments advanced by the advocates of magmatic origin is that there is in most cases a transitional phase of pyrrhotite-norite between the norite proper and the ore, and that this merges gradually into pure norite on the one side and into ore on the other. The fact that the ore bodies terminate fairly abruptly against the footwall rocks and fade out into the hanging wall norite is an argument against a hydrothermal origin and in favor of magmatic segregation. Howe has shown that in the Creighton mine this is a mechanical fading out and not a petrographic one as contended by Coleman. Specimens examined by the writer support a part of Coleman's contentions and indicate that while the main ore bodies fade out mechanically beyond them there is pyrrhotite-norite in which the pyrrhotite gives every appearence of being an original constituent of the rock. Knight, on the other hand, states that the granite, greenstone, and graywacke of the footwall are also spotted with sulphides in a manner similar to the pyrrhotite norite. It is clear, however, that the larger part of the ore bodies are in the norite and that there is a greater proportion of fading out into norite, whether mechanical or petrographical, than into the footwall rocks. The statements of Howe and Knight just quoted, invalidate to considerable extent the strength of the argument of fading out as a proof of magmatic segregation.

The uniformity and monotony of the ores and minerals over such a wide area in Sudbury is suggestive of an igneous origin. It is difficult to understand how ores deposited from solutions

which must necessarily be subject to fluctuating conditions of composition, concentration, temperature, and pressure could be so uniform all around the norite intrusive.

The indisputable evidences of water action as shown in many of the deposits is explained by the advocates of magmatic segregation by a later rearrangement by hydrothermal waters released from the magma during its solidification. By these solutions the valuable minerals are assumed to have been dissolved, transported, and redeposited in other places along with typical hydrothermal minerals, thereby bringing about a concentration of the ores, but by no means accounting entirely for the origin and position of the present ore bodies.

In all of his writings Coleman has emphasized the marginal position of the ore bodies with respect to the intrusives, and has pointed out that the largest ore bodies are where bays of norite project into the country rock or on offsets from such funnel-like bays. These points are used as one of the arguments for magmatic segregation. This marginal distribution is difficult of satisfactory explanation by any other than the magmatic theory and is one of the strongest points in its favor. It may be pointed out, however, that a more or less marginal occurrence of hydrothermal pneumatolytic ore bodies around intrusives is not unusual, for example, most tin deposits have a marginal position with respect to the intrusive.

The offset deposits extending outward from the funnel-like bays in the bottom of the norite are also used by the advocates of the igneous origin as suggesting magmatic segregation. Coleman[43] considers them to have been formed by a shattering of the underlying rock produced by its "collapse during the removal of the molten rock from beneath and also by the mechanical action of the laccolithic sheet spreading out above." These fractures are believed to have "drained" off the molten sulphides and norite, thereby giving rise to dike-like forms of norite and ore constituting the offsets. He states:

> The fissures and devious channels between the blocks would be flooded by the highly fluid norite and ore acting under the pressure of

[43] Can. Dept. of Mines, Mines Branch, No. 170, p. 36, 1916.

three miles of overlying magma and solid rock. The bottom norite highly charged with sulphides entered and filled every existing channel and forced its way in places through belts of shattered and weakened rocks enclosing many fragments torn off on the way.

Examination of this explanation discloses a weakness in its advocacy for magmatic segregation.

If the fracturing took place due to the removal of the magma beneath, or by the mechanical action of the overlying sheet, it must have taken place shortly after the intrusion of the nickel eruptive. Such fractures then would be expected to be filled first by the original undifferentiated magma, since differentiation in situ such as occurred in the nickel eruptive could not have taken place immediately, and considerable time must have elapsed before the norite and sulphides were segregated at the bottom in a position to enter the underlying fractures. Thus one must conclude that the fractures must either have first been filled by such a magma and later displaced by the basic phase, or, that the fractures were delayed in their formation until just the proper moment when the differentiation has proceeded sufficiently that the norite and sulphides were segregated at the bottom, or, that offsets cannot properly be accounted for by the explanation given.

The first two possibilities do not seem probable. If the fracturing be presumed to have resulted from the intrusion and the undifferentiated magma once entered these long narrow dike-like openings, where cooling would take place rapidly, it seems improbable that it could later be displaced entirely by a differentiated product of norite and ore without some evidence of the undifferentiated magma being left behind for it is clear that, due to the rapid cooling or freezing of magma on its walls, the outermost portion represents the undifferentiated magma. There is evidence in the fine-grained character of the norite near its margins the rapid cooling has taken place. Yet as far as can be learned there is no evidence of any undifferentiated magma or any indication that the fractures were first filled by such an undifferentiated magma. The very fact that the norite and ore have markedly fine-grained marginal phases indicates their contact with relatively cold rocks, and this would not be expected had differen-

tiation taken place in situ where the walls would become highly heated long before differentiation had proceeded sufficiently far to bring the differentiated norite and ore to the outside. Coleman[44] uses this chilled edge of ore and norite as a proof of magmatic segregation. While it certainly indicates, or at least strongly suggests, that the ore was in a molten condition, it does not favor the theory of magamtic segregation as much as it favors the modified theory of magmatic differentiation advanced by Howe.[45]

Its fallacy as an argument for segregation is further shown by Knight's findings that the granite footwall against which the ore in the Creighton is presumed to have been cooled is later in age than the norite. It is therefore proof that the ore must be later in age than the norite. The other possibility, mentioned above, seems too delicate an adjustment to be probable that the fractures should just open up at the particular phase of the completion of differentiation ready to receive the lower basic differentiate of norite and sulphides. Thus it would appear that the offset deposits cannot be assumed to have been formed as explained by Coleman and therefore are no argument in favor of magmatic segregation.

Another argument advanced by Coleman and others in favor of magmatic segregation is the ore breccia, so much described by all who have written on Sudbury, in which fragments of other rocks are enclosed by ore and norite. This is considered by Coleman[46] as "due to the faulting and smashing of the underlying rock owing to the motions of the nickel bearing magma in reaching the present position," and by "the bottom norite highly charged with sulphides . . . enclosing many fragments torn off on the way. Doubtless there was much grinding of one surface upon another in the process, accounting for the many rounded boulder-like fragments enclosed in the ore."

If the ore be assumed to have been formed by magmatic segregation then a considerable time must have elapsed between the

[44] *Op. cit.*, pp. 33 and 37.
[45] *Op. cit.*
[46] *Op. cit.*, pp. 34 and 36.

segregation and the first intrusion of the magma. For a marginal segregation of ore to have taken place either by gravity, convection, sinking crystals, or any other method, the magma of sulphides must have been in a relatively quiet of passive state and incapable of vigorously tearing off great quantities of fragments from the walls. Differentiation postulates a quiescent rather that vigorously moving magma. Also the fragments of rock in ore cannot readily be explained according to Coleman's idea for the reason that although the motions of the nickel-bearing magma, in reaching its present position, would probably enclose fragments torn off on the way. These fragments would be contained in the undifferentiated magma and not in that portion (the ore) which could not at this stage have been differentiated. Therefore the breccia in the view of the writer is opposed to magmatic segregation of ore in situ.

HYDROTHERMAL ORIGIN.

Dickson, as the first strong advocate of the hydrothermal origin based on microscopic work, finds several features irreconcilable with a magmatic origin, which in his opinion indicate the deposits were formed by hydrothermal agencies.

The microscopic evidence which he finds of replacement of the rock forming minerals by sulphides after hornblende and as a network of veinlets, strongly suggests that they were carried in solutions.

The development of secondary hornblende in the vicinity of the ore and the more complete alteration of the rock where replacement by sulphides has been more complete is another argument strongly favoring hydrothermal origin.

The presence of secondary quartz and calcite in the ore, but scarcer at a little distance from it, further suggests some relation between the ores and hydrothermal solutions. The amounts of these minerals are very subordinate to the sulphides of the camp as a whole, but in the one or two mines play a prominent part.

The widespread brecciation and shearing in which ore cements rock fragments and occurs along shear planes is certainly a strong

argument against magmatic segregation, but on that account is not necessarily an argument in favor of hydrothermal origin, as applied by Dickson, for it may apply equally well to the modified magmatic hypothesis proposed by Howe. The angular shape of the included rock fragments is considered by Dickson to be difficult to imagine on the basis of magmatic segregation. It would be equally difficult to imagine them having an angular form if they are residuals of a rock that had been replaced by ore by means of solutions. Replacement nuclei are usually smoothed and rounded by the replacing solutions.[47]

Again, Dickson uses as arguments in favor of hydrothermal origin the abrupt change so often noticed from massive sulphides to barren rock; that sulphides are practically lacking in the rock a short distance away from the ore, and that included rock fragments are comparatively free from ore, except in veinlets. These points are certainly opposed to a magmatic segregation, but do not necessarily indicate hydrothermal origin. The concentration of copper however in the form of veinlets traversing norite and pyrrhotite suggests solutions.

Thus Dickson's paper on the whole produces many arguments which oppose magmatic segregation, but do not necessarily uphold the hydrothermal origin. It also gives many arguments which indicate that hydrothermal solutions have been a factor in the formation of the Sudbury ores.

The work of Campbell and Knight[48] also suggests the hydrothermal origin in showing that the sulphides occur later than the rock silicates and in the definite order of pyrrhotite pentlandite, and chalcopyrite. Further the replacement of one sulphide by later sulphides and the replacement, rounding off, and filling of fractures of rock silicates by sulphides, suggest hydrothermal solutions.

A further appeal for a hydrothermal origin is to be found in Knight's latest contribution,[49] where the chief argument is that

[47] Irving, J. D., ECON. GEOL., Vol. 6, p. 527, 1911.

[48] "Microstructure of Nickelliferous Pyrrhotites," ECON. GEOL., Vol. 2, p. 350, 1907.

[49] "Origin of the Sudbury Nickel-copper Deposits," *Eng. and Min. Jour.*, Vol. 101, p. 811, 1916.

the magmatic segregation theory "is untenable owing to the structural and age relationship of the rock." It is shown, for the Creighton mine, that the "molten sulphides could not have settled to the bottom of the norite magma and rested on the granite footwall, for the very good reason that the granite was not there when the norite was erupted." Since ore penetrates the granite, and Knight shows the granite intrudes the norite, it is clear that the ore must be later than both norite and granite, and cannot therefore be a segregation from the norite. Knight's work demonstrates this point very clearly. These structural relations of the granite and norite have led Knight to conclude that not only is the magmatic segregation theory untenable, but the ores were formed in "a period of ore formation, during which solutions circulated along and near the contact of the granite and norite and deposited the nickel and copper sulphides which form the ore body."

While the structural relation of the granite and norite, brought out in this theory, deals a fatal blow to the magmatic segregation hypothesis, it does not necessarily follow that because a rival view is vanquished, the conclusion of a hydrothermal origin is the only alternative, for it supports Howe's modified magmatic theory just as much as the hydrothermal.

Knight also emphasizes the occurrence of ore in the Worthington mine which by its structure and mineral composition indicates hydrothermal action. All writers agree that the Worthington ores have been affected, if not largely formed, by solutions.

Knight's evidence that the sulphides mix with older greenstone and graywacke and younger granite in the same manner in which they mix with the norite certainly argues against a magmatic segregation, but again an argument against one theory does not support an opposing theory, unless there be positive evidence in its favor as well.

The writer agrees with Knight in so far as he shows the magmatic segregation hypothesis to be untenable, but fails to find in his arguments positive evidence actually supporting a hydrothermal origin for all of the deposits. Until such is forthcoming

the writer concludes that Knight's evidence supports Howe's modified magmatic hypothesis as much as the hydrothermal.

MODIFIED MAGMATIC ORIGIN.

Howe's interpretation[50] of the occurrence of the Sudbury ores differs somewhat from that of other observers. He found that in the Creighton mine there is no gradation from ore to norite in the petrographic sense, but there is a gradation due to a mechanical mixture of ore and rock. He considers that the intimate mixture of fragments of granite, greenstone, and norite in the ore precludes a metasomatic origin and that the microscopic work strongly suggests the sulphides were originally introduced in a molten state. To explain all these conditions he propsed the interesting modification of the magmatic hypothesis which accounts for the ore as having been introduced in a molten condition through a differentiation in the magmatic reservoir, after the norite had cooled. Thus the ore would be considered as a magmatic differentiation product though not a magmatic segregation in situ.

This igneous theory certainly accounts for the ore breccia, in which fragments of rock are cemented by ore, and explains the numerous veinlets of ore which cut across rock fragments and penetrate the footwall rocks. The offset deposits may also be readily explained by this theory. It accounts for those many troublesome arguments already considered which the advocates of the hydrothermal theory have brought against the magmatic segregation hypothesis and applied as points in favor of the alternative hydrothermal theory. As pointed out previously an argument against the magmatic segregation theory does not necessarily imply that it favors the hydrothermal theory. This modified theory of Howe's explains many such points that are equally incompatible with the hydrothermal hypothesis.

The evidence produced later by Knight[51] that the footwall granite at the Creighton mine intrudes the norite does not in-

[50] "Petrographical Notes on the Sudbury Nickel Deposit," ECON. GEOL., Vol. 9, p. 503, 1914.

[51] *Op. cit.*

validate Howe's hypothesis. On the contrary such evidence is directly in keeping with it if the ore be regarded as having been intruded after the granite, thus placing it in the same age relation to the norite and granite as does Knight in his hydrothermal theory.

While Howe's hypothesis relieves both the magmatic and hydrothermal theories of many objectionable features, it does not account for the marginal position of the ore bodies with respect to the norite. One would expect if the sulphides were intruded in a molten condition later than the norite that they would not necessarily have any relation whatever to the margins of the norite, while the magmatic segregation postulates such a marginal position.

Inasmuch as Howe's paper deals chiefly with petrographical notes of the Sudbury region he does not sum up or discuss evidence in favor of or against his suggestive hypothesis; consequently he offers no explanation as to how his hypothesis would reconcile the marginal position of the ore bodies.

The structural relations at the Creighton mine, which Howe advances his modified magmatic hypothesis to explain, might also be accounted for by the magmatic segregation theory if in that process the segregated sulphides be presumed on account of their lower fusion points to have remained molten longer than the hanging wall norite. They might then intrude and enclose fragments of already solidified norite.

MODIFIED HYDROTHERMAL ORIGIN.

Tolman and Rogers[52] believe they reconcile the almost diametrically opposite views of the supporters of the hydrothermal and magmatic segregation theories. They believe that the ores are magmatic, yet formed by means of "mineralizing solutions" or mineralizers. They state that the sulphides surround, cut across, and replace the rock silicates and are therefore later than them, and they present microscopic evidence which they interpret to indicate that the sulphides were formed before the hydrothermal

[52] *Op. cit.*, p. 15.

alteration of the rock silicates. This is based on their observation that pseudomorphs of tremolite and possibly talc were formed as a hydrothermal alteration product after hypersthene, and that chalcopyrite, which cuts across the pseudomorphs in the form of veinlets, has not wandered into the cracks of the tremolite, and is therefore earlier than the alteration. They would thus place the period of mineralization after the consolidation of the norite, and before the hydrothermal solutions, which emanated as an after effect of the intrusion. They consider that the ores are not magmatic in the usual sense, because they are later than and replace the rock silicates. They believe that they were deposited by "mineralizing solutions" because of the regular order in which the sulphides are deposited one after the other, and the fact that one replaces the other.[53] They do not consider them to be ordinary hydrothermal deposits because the formation of the sulphides is thought to precede the hydrothermal alteration of the rock silicates. They also think the sulphides could not have been intruded in a molten state as suggested by Howe, because there is no evidence of the metallic silicates and reaction rims which they believe should result by contact of the molten sulphides with the rock silicates and earlier sulphides.

In retaining the term "magmatic" to fit in with their conception of the Sudbury deposits, they deprive it of its customary usage. Accepting for the moment the interpretation of the ores given by Tolman and Rogers, there is more justification in calling them hydrothermal rather than magmatic, inasmuch as they are considered to have been transported and deposited by mineralizing solutions in the same manner that any hydrothermal deposits have been formed. They separate this type from the hydrothermal hypothesis advocated by others, because they find a lack of alteration of rock silicates accompanying the deposition of the ores. While this is clearly a distinction in the effects of hydrothermal mineralization, it does not appear to the writer to justify a different type of process, for the customary usage of hydrothermal processes does not imply rock alteration as an essential part of the process.

[53] *Idem*, p. 15.

The writer is thus unable to see in what way the arguments of Tolman and Rogers establish any but a hydrothermal origin for the Sudbury ores, and it is not clear to him how their hypothesis reconciles "the almost diametrically opposite views" of the magmatic segregation and hydrothermal processes.

Their hypothesis certainly does not account for the marginal position of the ore bodies with respect to the intrusive nor does it give any explanation for the connection between ores of this type and the norite gabbro magmas. Tolman and Rogers lay particular emphasis on the replacement of the rock silicates by the sulphides while Barlow, Dickson, Coleman, and others in their microscopic descriptions consider that the sulphides are original constituents in the rocks and have not formed by replacement. Howe's careful microscopic work[54] revealed only one certain instance of replacement of rock silicates by sulphides. An examination by the writer of several thin sections and polished specimens revealed only two instances in which replacement seemed certain to have taken place. It must be concluded then that the abundant evidence of replacement noted by Tolman and Rogers cannot be typical of all the Sudbury ores. In view of the evidence shown by others it is incorrect to apply broadly the theory of replacement to explain all of the Sudbury ores.

SUGGESTED MODIFIED HYPOTHESIS FOR ORIGIN OF SUDBURY ORES.

From the above discussion of the different views advocated for the origin of the Sudbury ores it may be seen that their genesis is complex and that there is much conflict of opinion regarding them, both as to interpretation of data and observations. The opposing hypotheses set forth an array of arguments and facts that is persuasive when one hypothesis alone is considered. All of them present plausible and convincing points which are not explained or set aside by the opposing arguments and are worthy to stand in any consideration of origin of the Sudbury deposits. It thus appears to the writer that an hypothesis that would embrace the convincing arguments of the opposing views, if in

[54] ECON. GEOL., Vol. 9, p. 511, 1914.

agreement with other observations, would be a correct one. Accordingly he presents a modified hypothesis, which follows Howe's and embraces and combines some of the features of the others:

A magmatic reservoir may be presumed to have underlain the Sudbury region and to have contained a magma of probably intermediate composition. Differentiation of this magma in the reservoir took place, but before it was completed a portion of it was extruded to form the "nickel eruptive." The extruded portion then continued to differentiate in its upper chamber and gave rise to the differentiated intrusive as described by Barlow, Coleman and others with micropegmatite grading downward into norite. The sulphides, chiefly pyrrhotite, contained in this magma, became segregated at the lower portion of the norite, thereby accounting for the pyrrhotite norite and perhaps a minor part of the ore bodies. In the meantime differentiation proceeded in the remainder of the magma in the reservoir below, and the magma may be considered to have divided itself into an acid and basic portion, much as did the portion previously extruded.

A further extrusion then took place, and the acid portion was injected between the already solidified norite and the greenstones, a probable line of weakness. Upon consolidation it gave rise to the later granite described by Knight. Following this, the process as conceived by Howe may be considered to have taken place, and a further expulsion of the basic portion from the reservoir occurred. This consisted of a magma overloaded with sulphides which, by consolidation, formed the greater part of the ore bodies. The peculiar pegmatitic inclusions described by Howe may represent some of the rock matter that was extruded with the sulphides. Still later expulsions would give rise to the dikes which cut the ores and previously intruded rocks

Where igneous intrusion and differentiation has taken place, a usual after effect representing the final extracts is hydrothermal solutions. The solutions from the Sudbury magma reservoir, similar to those which have formed most ore deposits, would contain some metallic minerals, and their circulation along the lines of previous intrusions might superimpose on the previously

formed deposits those hydrothermal effects described by Dickson, Knight, Tolman and Rogers, and others.

This modified hypothesis would thus explain the ores by magmatic segregation, magmatic differentiation in the magma reservoir, and hydrothermal action, but the greater part of the ore bodies would be accounted for by Howe's hypothesis of differentiation in the reservoir and intrusion as a sulphide magma. The sequence of igneous events might be diagrammatically expressed as follows:

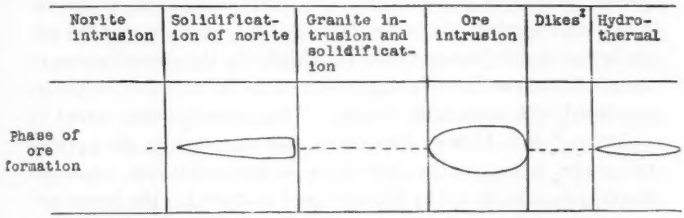

FIG. 16. The dikes which cut the ore are placed in this table previous to the hydrothermal solutions which brought in those typical hydrothermal minerals, but, in the absence of definite statements concerning these relations, this position may be incorrect and they may have been intruded during or after the period of hydrothermal mineralization.

In the hypothesis proposed above there remains the difficulty of accounting for the marginal position of the ore body. This position may have been brought about by the intrusion of the molten sulphides with some rock matter, along the zones of easiest access. The contact between the norite and adjacent rocks would probably be places of weakness favorable for such intrusion. This contact may have been rendered especially weak by fracturing brought about by the collapse of the floor or by the withdrawal and settling down into its conduit of the magma after its intrusion, thus causing a slumping of the intruded mass and its overlying sediments, giving it its spoon-like form. Such slumping would cause a rupturing along the margin of the intrusive and give rise to zones of weakness where later intrusives, such as an intrusion of molten sulphide with some rock matter,

could take place. Thus the earlier sulphide intrusions would, in part, be superimposed upon the earlier sulphide segregations.

DISCUSSION OF PROPOSED HYPOTHESIS AND RELATION TO OTHER HYPOTHESES.

The proposed hypothesis would account for the pyrrhotite-norite described by Barlow, Coleman, and others and for the sulphide particles so widely distributed along the margin of the norite by the first phase of mineralization or the magmatic segregation which took place in the nickel eruptive after its extrusion. The main marginal ore bodies such as the Creighton and the offset bodies would be accounted for chiefly by the second phase of mineralization or Howe's suggestion of the intrusion of sulphides combined with some rock matter. Thus the objection raised by Coleman,[55] that Howe's hypothesis does not explain the pyrrhotite norite, is met by the first phase of mineralization, while the second phase as shown by Howe would account for the brecciated character of the ore bodies in which fragments of rock are surrounded and penetrated by the sulphides.

This brecciated character alone would not be sufficient support for Howe's theory. As previously mentioned such a structure could well be formed according to the segregation hypothesis, if the sulphides, on account of their lower fusion point, remained fluid longer than the norite and penetrated the consolidated norite, thus including and surrounding particles of it. However, since Knight shows the granite to be later than the norite and the ore is later than the granite, then the ore is obviously later than the main norite intrusion and therefore could not be explained by segregation, but under these circumstances is readily explained by Howe's hypothesis.

As previously pointed out by the writer on page 408 the fact that the narrow dike-like openings are filled by sulphides and not by the original undifferentiated intrusive is an objection to the magmatic segregation but is readily explained by Howe's part of the hypothesis. Also the inclusions of rock in ore as pointed out on page 22 would be expected in undifferentiated magma and

[55] ECON. GEOL., Vol. 10, p. 390, 1915.

not in the differentiated sulphides, according to the segregation hypothesis. They would however, be expected to occur in the sulphide in the same way that fragments of invaded rock are contained in any intrusive under the sulphide intrusion hypothesis. In fact the matrix of ore enclosing fragments of rock, pictured by Coleman on Plate XVIII. of his article,[56] would appear to be a rock intrusion breccia if it were not stated that the matrix is pyrrhotite. Also Howe[57] points out that it is difficult to understand how the fine-grained border texture of the norite could develop under the segregation hypothesis, but such is readily understood by considering the sulphides to have been intruded between the previously formed chilled edge of the norite and the underlying rocks.

The puzzling siliceous inclusions in the sulphides described by Howe[58] and discussed by Coleman[59] and Tolman and Rogers[60] are considered by Howe to be inclusions of footwall granite, and by Coleman and Tolman and Rogers to be differentiates of the norite. Taken into consideration with the hypothesis outlined above they might also be explained in harmony with both Howe and Coleman as the consolidation of some of the rock magma which accompanied the intrusion of molten sulphides. Such a magma would undoubtedly contain characteristics of the granite footwall earlier differentiated from it below, and of the norite still earlier differentiated from it in the magmatic reservoir. In the same way may be explained the constant inclusion in the pyrrhotite of small amounts of rock silicates such as pyroxene and plagioclase mentioned by Coleman.[61]

The offset deposits can be readily explained by Howe's part of the hypothesis, but as pointed out on page 409 are difficult of explanation by the segregation theory. As Howe points out[62]

[56] "The Nickel Industry," Can. Mines Branch, No. 170, p. 49, 1914.
[57] *Op. cit.*, p. 515.
[58] *Idem*, p. 518.
[59] ECON. GEOL., Vol. 10, p. 390, 1915.
[60] *Op. cit.*, p. 26.
[61] Can. Dept. of Mines, Mines Branch, No. 170, p. 30, 1913.
[62] ECON. GEOL., Vol. 9, p. 522, 1914.

"intrusion by sulphides is essentially the explanation given by Coleman to account for certain of the offset deposits."

The observations of Dickson's[63] that the sulphides are best developed where crushing is most pronounced and that ore prevailingly occurs as a cement for rock fragments and along shear planes, support Howe's part of the hypothesis and are not explained by the segregation theory. While Dickson presents these arguments in support of the hydrothermal theory, the angular character of the included fragments suggests inclusions by an intrusion rather than nuclei of unreplaced rock. The abundant evidence, presented by Dickson and others, of veinlets of sulphides seaming included fragments of rocks and penetrating mineral cleavages would be expected from sulphide intrusion as well as from hydrothermal action so that the proposed hypothesis combines those features advocated for the hydrothermal origin and antagonistic to the segregation theory.

The remarkable freshness of the norite surrounding the ore is noted by Barlow, Walker, Coleman, Howe, Tolman and Rogers, and others.[64] This feature may be readily understood if the ore be considered as an intrusion but is not readily explained if all the ores were formed by means of hydrothermal agencies, for, as Coleman points out, the susceptible hypersthene would surely succumb to alteration. While in many places hydrothermal alteration of the norite is almost entirely absent, some effect of it is shown by the alteration of the pyroxenes in most parts of the district, particularly in the offset deposits. As compared with the universally widespread rock alteration accompanying ore deposits of unquestionable hydrothermal origin, however, the paucity of such alteration in the Sudbury deposits renders it difficult to accept a hydrothermal origin to account for all of the ores.

Also Howe[65] and Tolman and Rogers[66] show that the hydrothermal alteration is later than the formation of the sulphides.

[63] *T. A. I. M. E.*, Vol. 34, p. 59, 1903.
[64] *Op. cit.*
[65] *Op. cit.*, p. 513.
[66] *Op. cit.*, p. 33.

Still another point that suggests an igneous origin for most of the ores in preference to a hydrothermal one is the absence of the gangue minerals that usually accompany hydrothermal ores. With an igneous origin the only gangue to be expected would be the rock accompanying the sulphide magma such as is found in the ores.

The replacement of rock silicates by sulphides is strongly urged by Dickson, Tolman and Rogers, and Campbell and Knight in favor of hydrothermal agencies. On the other hand, Howe, Barlow, Walker, and Coleman find little evidence of replacement. The writer's examination by means of thin section and polished specimens indicated a very minor amount of replacement. There thus appears to be some ore that is not a result of replacement and other ore that has replaced the rock silicates. The writer observed under the microscope two instances in which rock silicates were embayed by sulphides similar to the embayment so commonly observed in quartz phenocrysts in a granite porphyry. Whether this embayment is due to resorption or replacement is difficult to determine, but whatever the process in detail it is certain the embayment or resorption of quartz phenocrysts is a magmatic phenomenon and not a replacement brought about by later circulating solutions. It may be that much of that which is called replacement of the norite by sulphides has been brought about by a similar process and need not be attributed to hydrothermal solutions. It is conceivable that the sulphide magma with its small amount of rock magma could corrode or replace the rock silicates giving rise to much the same effect produced by hydrothermal solutions. It is well known that in smelter practice molten matte, mostly sulphides, readily corrodes siliceous and basic linings of converters. Tolman and Rogers[67] lightly dismiss corrosion as a possibility because they consider it "should produce metallic silicates by reaction" and "no such metal-bearing slag is found, and the agency that brought in the sulphides removed the dissolved silicates, all of which indicates active mineralizers." It seems more probable if a metal-bearing slag had

[67] "A Study of Magmatic Sulphide Ores," Pub. Stanford Univ., p. 15, 1916.

formed that it would have been carried along and removed by the heavily charged sulphide magma. It is suggested that the presence or absence of such a slag would depend entirely upon the condition of the magma, and if the conditions were in such delicate adjustment that the magma were just about to solidify when the slag was formed, a reaction rim of metallic silicates might form, otherwise not. Is it also not possible that the corroded silicates of the norite may have been absorbed by the sulphide magma and combined with a portion of its material to form some of the inclusions or silicates in the ore? It appears to the writer that our knowledge of replacement or corrosion of silicates by a heavily charged sulphide magma is insufficient for such a possibility to be lightly dismissed on account of the absence any metal-bearing slag in the ore. Such absence would not necessarily indicate the action of solutions.

The advocates of a hydrothermal origin point out that among the sulphides pyrrhotite is the oldest and is cut and surrounded by pentlandite and chalcopyrite. The last two have a common habit, but chalcopyrite is believed to be slightly younger than the pentlandite. This order of succession of sulphides is advanced in support of deposition by solutions. The minerals of a granite occur in a successive order of formation, but that does not imply successive deposition by solutions. The sulphide intrusion may be considered a magma overloaded with sulphides, and it is to be expected that its solidification would show a regular order similar to the minerals of any rock. Also in this connection Howe suggests that the order "would seem to be better explained by the nearly simultaneous cooling of the different sulphides that had previously separated as distinct mineral compounds, non-miscible, though still molten." In this way the last to crystallize would penetrate the earlier sulphides.

Thus many of the arguments advanced to support the hydrothermal theory substantiate Howe's part of the proposed hypothesis equally well, and other of the arguments are explained readily by either theory. Certain features, however, such as the occurrence of typically aqueous minerals as calcite, secondary quartz, marcasite, galena, and others, and the alteration of the

pyroxene, are clearly indicative of hydrothermal origin. These effects are attributed to the final or hydrothermal phase of mineralization as indicated in the proposed hypothesis. While their widespread effect is recognized, abundant products of hydrothermal deposition and alteration are to be found only in the offset deposits, notably the Worthington Mine. The writer believes that only a minor part of the ore bodies has been contributed by the hydrothermal solutions and that their work has been chiefly an unequal permeation of the rock producing alteration; the contribution to certain of the offset deposits of the uncommon and untypical aqueous minerals; probably an enrichment of some of the offset deposits in copper and the precious metals, and the rearrangement of some of the previously formed sulphides, such as has been mentioned by most investigators.

The reasons why hydrothermal processes are limited to the above features and are not concluded to account for all of the deposits have already been considered. It may be seen that hydrothermal mineralization of this nature superimposed upon previously formed ores would confuse characteristics of the previous processes, and a study of those places most affected would give rise to the impression that all of the ores have been formed by hydrothermal agencies. The hydrothermal origin of the Sudbury ores has attained in the literature a position hardly justified, because observations antagonistic to the segregation hypothesis have been applied as convincing arguments in support of it as a single working hypothesis when they are capable of more than one interpretation if applied to multiple working hypotheses.

SUMMARY.

A review of the literature indicates that the origin of the Sudbury ores is a controversial question that is by no means settled as yet. One school of geologists advocates an origin by magmatic segregation whereby sulphides have settled by gravity to the bottom of the intrusive sheet of norite and collected in favorable places to form ore bodies; another school advocates an origin by means of hydrothermal agencies. A modification

of the magmatic theory has been advanced to explain the ores by differentiation in the magmatic reservoir below and intrusion in the form of molten sulphides. A modification of the hydrothermal theory would account for the ores as having been introduced at a late magmatic stage as a result of mineralizing solutions without the formation of secondary silicates. Plausible and convincing arguments for all of these hypotheses are advanced, yet no one theory will explain adequately all of the observed phenomena, nor will it hold against some of the antagonistic arguments of the others. It has appeared to the writer from his discussion of the different views that the Sudbury phenomena cannot be accounted for by any single hypothesis, but can be explained readily by an hypothesis of progressive mineralization which embraces parts of all of the previously advanced hypotheses. He therefore advances the hypothesis that the Sudbury deposits were formed in minor part by magmatic segregation in situ from the nickel eruptive, thereby accounting for the pyrrhotite, norite and some of the marginal ore; in greater part by an intrusion of magma overcharged with sulphides formed by differentiation in the magmatic reservoir beneath, thereby accounting for the greater part of the main marginal bodies and the offset deposits; in minor part by hydrothermal solutions that circulated as an after effect of the intrusions and produced the hydrothermal alteration of the rocks, the later rearrangement of the minerals and the deposition of the typically aqueous minerals such as occur notably in the Worthington mine.

This hypothesis is proposed with more security, since it does not conflict with observed evidence and harmonizes many of those conflicting arguments advanced for single hypotheses which have become controversial points among advocates of other hypotheses.

MAGMAS AND SULPHIDE ORES.

A. P. COLEMAN.

Oxygen and sulphur seem to play a somewhat similar part in their combinations with the metals, and compounds of both occur associated with eruptive rocks in ways which suggest that they were originally included in the molten magma; yet certain geologists make a wide distinction between oxides and sulphides in their interpretation of the field relations of these two types of ores. Every one accepts the rôle of oxides as highly basic portions of magmas which may be segregated when cooling takes place. No one disputes that the titaniferous magnetites and ilmenites associated with gabbros and anorthosites have been parts of the fluid magma from which these rocks were formed; and yet protests are raised against a similar interpretation of sulphides or iron, copper and nickel associated with pyroxenites, dunites and norites. The separation of oxide ore bodies from a basic, or even somewhat acid magma, as in the case of the Kiruna magnetites, seems to arouse no hostility; but in some minds the suggestion that the Sudbury sulphide deposits have segregated from the norite with which they are everywhere connected seems to be instinctively objected to as if it were contrary to the laws of nature.

This prejudice against the magmatic origin of sulphide ore deposits is the more surprising when one recalls that the source of the sulphides themselves is always sought in eruptive rocks. For example, we are astonished that the zinc and lead sulphide ores of Missouri cannot be traced certainly and directly to some mass of eruptive. Even if we incline to account for them as derived from marine rocks, we assume that the sea obtained its sulphates from the leaching of former eruptive rocks. The great majority of metallic ores can be traced with certainty through the action of circulating waters to a source in some cooling eruptive

mass; and yet some geologists cannot bring themselves to believe that sulphides may accumulate directly through gravity at the lower edge of a cooling magma. To them hot waters are a necessary intermediary.

Questions connected with the theory of magmatic segregation of sulphide ores have been discussed recently by several authorities, with conclusions that vary widely. Goodchild describes the Insizwa nickel ores of South Africa as undoubtedly due to gravitational segregation,[1] and compares them with the nickel deposits of Sudbury. Tolman and Rogers also have made a very careful study of the subject, as far as this can be done by laboratory methods, and their plates give admirable illustrations of the final relations of the different minerals to one another in specimens from most of the known regions; but they seem to have been unfamiliar with the field geology of Sudbury, the most important of all. Their results are interesting as an attempt to harmonize the theory of magmatic segregation with that of replacement by hot solutions.[2] The latest account of the Sudbury deposits, by Knight in the recently published report of the Royal Ontario Nickel Commission, inclines strongly to the aqueous theory. He evidently intended to present the matter impartially and summarizes the usual arguments for the magmatic origin of the ores, but his leaning toward an aqueous origin is very evident. A little later in the same report the Alexo deposit of northern Ontario is unhesitatingly described by Baker as due to magmatic segregation, though his explanation differs somewhat from the one usually given for the Sudbury deposits. These writers express three entirely distinct and even contradictory views of the origin of sulphide nickel ores, two favoring the theory of magmatic segregation, two occupying an intermediate position, and the fifth favoring the theory of replacement by hot waters.

Knight discusses the matter extensively in a ponderous and on the whole excellent public report and may be supposed to have presented the strongest evidence possible for the theory of hydro-

[1] "The Economic Geology of the Insizwa Range," Institution of Mining and Metallurgy, 1916.

[2] "A Study of the Magmatic Sulphid Ores," Leland Stanford Univ. Pubs.

thermal replacement of rock forming minerals in the case of the Sudbury nickel deposits. It is proposed here to examine his evidence to see how conclusive it is.

So far as I am aware Knight's first published work on the Sudbury deposits had to do with the microscopic study of polished sections of the ores, in which a definite order of succession of the minerals was worked out and interpreted as due to circulating hot waters. The metallographic studies of Campbell and Knight were excellent, and their results are in many respects of permanent value; but it may be observed that most of the sections they examined were from offset nickel deposits, where there has been a great amount of faulting, weathering and rearrangement of the materials. That circulating water had much to do with the present condition of these offset ores no one doubts; and it is not surprising that Knight and others who approached the study of the deposits from the metallographic side were impressed by the evidence they presented of water action.

In the study of a complicated set of phenomena one naturally begins with the simplest and least changed examples and not with the more modified and complicated ones. Among the Sudbury ore deposits there are some which are relatively simple and unchanged, such as the Creighton and other great marginal mines, and the search for the origin of the nickel ores should begin with them. If the Creighton ore body was formed by magmatic segregation, all the others, no matter how much they have been modified since, must be accounted for in the same way.

In reading Knight's description of the Sudbury relationships one is struck by his defensive attitude. For instance the statements of T. L. Walker, Barlow and the present writer in regard to the magmatic segregation of the norite-micropegmatite sheet with which the ores are associated are accepted only with the complaint that "one is not able to say that there is a gradual transition from basic to acid rock as one goes from the outer to the inner edge." The idea seems to be that the admission of magmatic segregation in the rock hints at the segregation of the ore bodies as well. The objection that the upper edge of the sheet is not quite so acid as the average micropegmatite leaves

out of account the fact that much stoping and digestion of the overlying sediments has been proved, which must have modified the composition of the upper edge. In regard to the lower edge also there is a curious suggestion that the norite sometimes has a "gigantic dike-like form," apparently another attempt to disarrange the magmatic machinery. This difficulty is easily met by the well-known proofs of faulting on a considerable scale along the southern nickel range. The objections to the segregation of norite from micropegmatite and to the sheet-like form of the eruptive are not pressed strongly; and to one who has worked in detail round the margin of the sheet have no weight whatever.

The arguments against the magmatic segregation of the ore bodies in general are given more formally, and are somewhat surprising. For instance the statement is made that in marginal deposits "the commercial ore bodies occur almost wholly in the rocks adjacent to the norite and not in the norite. The contact between commercial ore and norite is generally a comparatively abrupt one." Now the theory of magmatic segregation of ores by the aid of gravitation demands just this condition. The ores should be beneath the norite and in the hollows and fissures of the country rock. As to the second statement one finds a few pages later that at Creighton "some of the mineralized norite near the deposit contains from 1.5 to 2.5 per cent. of nickel and copper combined," showing that the gravitational separation was not complete.

To the statements of Barlow and myself that blebs of ore occur on a large scale in perfectly fresh norite where even the hypersthene is unchanged, the extraordinary objection is made that at some deposits "it is so badly decomposed and altered to a schist that it is difficult to distinguish it from other altered rocks." Surely the fact that some of the norite has been altered has nothing to do with the original condition of parts which are admitted to be "very fresh." This is an exact reversal of the correct line of argument. If large amounts of ore are scattered through perfectly fresh norite they must have been present in the magma before it cooled and crystallized.

The next objection is equally curious, namely, that quartz and

calcite occur with the ores at several of the mines, such as the Garson and Crean Hill, indicating the action of water. These mines were proved by the present writer to have been greatly faulted and shattered after they were originally formed as marginal deposits. These later changes have naturally permitted the circulation of water, completely altering the character of the ores. In the case of the Crean Hill mine the deeper workings, below the planes of faulting, show an ore body of the ordinary marginal character.[3]

Another singular argument against magmatic segregation at Creighton is this: "if the granite foot wall at Creighton is younger than the norite, then it was manifestly impossible for the sulphides to have settled from the norite upon this granite." But the granite has not been shown to be younger. Both Barlow and the present writer believed it to be older than the norite; but even if younger, of which Knight gives no proof, it is quite as possible for it to have pushed up beneath the ore body as anywhere else. In fact, as both Barlow and myself have shown, there are granites of more than one age in the region, some older and some younger, but they have no more bearing on the formation of the ore bodies than the greenstones, older norites, and diabases found as country rocks at most of the mines.

The suggestion that there "are too many notable exceptions to the statement that the largest ore bodies are found where bays of the norite project into the country rock" is quite incorrect. Of the two supposed exceptions noted the Crean Hill deposit is shown by the plans of the mine to be in a small, well defined bay. It is only the surface parts of the ore, which have been faulted inwards for 200 feet or more, which suggest the opposite. As to the other supposed exception to the rule Knight himself explains the deposit as not alone below the norite but actually in the granite beneath it. On the other hand not a single deposit is found at an inward bend of the norite.

Another objection brought against the magmatic theory is the brecciated character of the country rocks enclosed in the ore. Surely there must have been enormous crushing and brecciation

[3] "The Nickel Industry," p. 50.

of the rocks beneath when the great norite-micropegmatite sheet forced its way between them and the overlying sediments. This brecciation is visible almost everywhere beneath the norite, both where ore occurs and where ore is absent, and evidently has nothing to do with replacement of rock by ore. Knight's own figures of brecciated rock fragments from the Creighton mine show exactly what might be expected when the hot molten ore enclosed them. They were expanded and shattered and one can see how they drifted apart in the ore. His account shows that these blocks are perfectly fresh, which could not have been the case if hot solutions had attacked them, replacing rock minerals by ore.

The magmatic theory explains the facts perfectly, and the aqueous theory is quite incredible for such deposits as the Creighton with perfectly fresh granite and older norite as fragments in the ore and forming the floor beneath, while the hanging wall consists of pyrrhotite-norite, often perfectly fresh also.

That hot water should replace millions of tons of norite and granite by ten million tons of sulphides, leaving even the smallest enclosed fragments fresh and unattacked, without depositing any of the usual gangue minerals, such as quartz or carbonates, and without a hint of banding or crustification is too much to claim. The facts are simply enough explained on the theory of magmatic segregation aided by gravity but impossible by any known hydrothermal method.

The cubic miles of pyrrhotite-norite above the marginal deposits, often perfectly fresh, as Knight admits, and extending for 2,000 feet away from the hanging wall of the Creighton mine, as he also admits, are surely inexplicable by aqueous action. In reality isolated blebs of ore, sometimes scattered one in a square foot or in a square yard, extend away beyond this limit.

It is hard to see how anyone, after a careful study of the Creighton ore body and its surroundings, can deny the strong probability, if not the certainty, that it was formed by settling out of the norite magma as matte settles from slag; and if this is admitted for the great and scarcely changed marginal deposits it must be admitted also for faulted marginal deposits, like those of

Crean Hill and Garson, where water has worked over and rearranged the materials, and for the offset deposits as well, every one of which is accompanied by more or less pyrrhotite-norite, still recognizable by its "pock-marked" character, though such easily changed rock minerals as the pyroxenes are now replaced by hornblende.

The immense amount of ore scattered as small isolated spots or blebs through the norite above the marginal deposits seems unaccountable by the ingeniously worked out theory of Tolman and Rogers also. These separate spots of ore enclosed in fresh norite and often separated from one another by several inches or even feet of rock could not have been introduced "at a late magmatic stage by a partial replacement of the silicate minerals." These sulphides must have been present when the rock itself cooled and consolidated, and no theory which does not account for the cubic miles of pyrrhotite-norite near the basic edge of the Sudbury eruptive sheet can be accepted as solving the problem of these greatest of all nickel deposits.

Most geologists who have studied the Sudbury region are satisfied to accept the theory of magmatic segregation aided by gravity, the ores settling down directly into the hollows and fissures of the rock beneath; but there is a possibility that the process was not quite so simple as this statement might suggest. Ernest Howe's idea that the ore of the Creighton mine came in as a later intrusive deserves consideration[4] and is supported by Baker's conclusion that the solid ore of the Alexo mine arrived later than the ore disseminated through the serpentine.[5] While this theory will not account for the pyrrhotite-norite and pyrrhotite-peridotite of the two regions it may well be added on to the usual theory to explain certain features of the deposits where solid sulphides come rather sharply in contact with the hanging wall. The sulphides fuse at a much lower point than norite and must have remained fluid long after it had become pasty or even solid. It is evident that there was much shifting and readjustment of the country rocks during and after the intrusion of the

[4] "Notes on Sudbury Nickel Deposits," ECON. GEOL., Vol. IX., No. 6, p. 517.
[5] "Rep. Roy. Ont. Nickel Commission," p. 232.

great sill, and one can imagine the jostling of the still liquid ore in one direction or another from time to time as the blocks shifted.

At a later stage, when the ore itself had solidified, further cooling would imply shrinkage and continued adjustments including some faulting, giving entrance in some places to hot waters producing chlorite, talc and other secondary minerals from basic rocks and depositing more or less calcite and quartz with occasional seams or masses of galena or sphalerite; features displayed in faulted marginal mines and also in most of the offsets. Under these circumstances the ores also would suffer some attack and the most susceptible of them, chalcopyrite, would be somewhat segregated along the sides of enclosed rock fragments or in the fissures due to fracturing or cooling of the country rock. Thus the faulted marginal deposits of Crean Hill and Garson, and the offset deposit of Copper Cliff are richer in copper than in nickel, unlike the scarcely modified marginal mines, such as the Creighton and Murray, which contain far more nickel than copper.

Last of all came fissures in both ore and rock filled with dikes of diabase which were rapidly chilled against the cold ore and have a glassy margin. These dikes have had no appreciable effects upon the ore bodies except to interfere a little with mining operations.

The sequence of events briefly sketched above is in good agreement with the theory of magmatic segregation under the influence of gravity but quite unintelligible on the assumption that all the ore deposits are due to hot circulating waters.

THE PETROLOGY OF RESERVOIR ROCKS AND ITS INFLUENCE ON THE ACCUMULATION OF PETROLEUM.

A. W. LAUER.

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INTRODUCTORY SUMMARY.

The recognition of petroleum in sedimentary rocks early led to the belief that it usually is not found where originally formed. The present "pools" indicate at least some migration from the beds of origin, with a subsequent accumulation in the rock formations where it now occurs.

The features which control this migration have long been disputed among geologists, and in the opinion of the writer insufficient attention has been paid to the part played by the porosity of the rocks. Consequently he undertook an investigation of rock openings in the hope that it might throw light upon this question.

The study consisted of an examination, supplemented by microscopic evidence, of suites of specimens obtained from oil-bearing strata at variable depths in oil wells widely scattered over the North American petroleum fields. Through the courtesy of the officials of the different oil companies, the geological surveys, and others, the writer has been singularly fortunate in obtaining specimens up to 9 inches in length, so that he feels considerable reliance may be placed on the data obtained from them.

The investigation of the specimens has been supplemented by a broad study of the causes of rock openings of all kinds and sizes.

The results reveal that porosity is not so much a matter of original interstitial openings, but that later induced openings have played a part hitherto insufficiently recognized. The result is to give more effectiveness to hydrostatic water action, and on these grounds plus a careful weighing of the merits of other theories proposed, the writer concludes for a defense of the anticlinal theory.

REVIEW OF PREVIOUS THEORIES.

To clarify the discussion and to present a summary of present views held by oil geologists, the theories of oil movement and accumulation now in the literature will be briefly reviewed. These include the anticlinal theory, the hydraulic theory, the theory of capillary concentration, the theory of selective segregation and gravitational separation, and the filtration theory. The

first four have grown out of attempts to reconcile the facts of oil occurrence to physical principles governing the movement of liquids through rock material while the fifth is developed from a slightly different viewpoint.

The Anticlinal Theory.

Probably the best statement of this theory in its present form, somewhat modified from the original developed by Orton, White, and others, is that by Griswold and Munn:[1]

"Whether the petroleum comes from within or from below the shales, it must pass through them, and to do this it must pass through the very small pores existing in those relatively impervious beds. The nature and cause of this movement are not understood. Capillary action and great rock pressure may be suggested as causes which aid in forcing the petroleum out from the shales, but there are not sufficient data on this subject to justify any scientific explanation. It matters little what is the ultimate source of the oil; the important facts are its occurrence now in the porous sandstones, its circulation through the rocks, and the conditions leading to its accumulation in commercial deposits."

"*Movement in Porous Rocks.* The porous rocks into which oil and gas enter may be dry, or they may be completely saturated with water. In most cases it is probable that a combination of these two causes exist—that the porous rocks are completely saturated with water up to a certain level, but above that point they are dry. The movement of the hydrocarbons through the rocks will not be the same in the two cases, and therefore each condition must be considered separately."

"If small quantities of oil and gas enter a dry porous rock at different points the oil will flow down as long as gravity is sufficient to overcome the friction and the capillary attraction. The gas will diffuse with the air or water-vapor contained in the pores of the rock."

"Oil and gas entering a porous rock that is completely saturated with water will be forced up to the top of the porous stratum by the difference in the specific gravity of the hydrocarbons and the water. Here the oil and gas will remain if the porous stratum be perfectly level, but if it has a dip sufficient to overcome the friction the particles of oil and gas will gradually move up this slope, the gas with its lower specific gravity occupying the higher places."

"In case the porous rocks are partly saturated a combination of these

[1] W. T. Griswold and M. J. Munn, "Geology of Oil and Gas Fields in Steubenville, Burgettstown, and Claysville Quadrangles, Ohio, W. Va., and Pa.," U. S. G. S. Bull. No. 318, 1907, pp. 13–14.

two actions will take place. The oil entering above the line of complete saturation will flow down to that line and the oil entering below will be forced up to the top of the completely saturated portion."

"The statements given above are based on the assumption that the oil-bearing rock is homogeneous throughout and that the oil will move with the same degree of freedom in every direction. This is rarely the case. Sandstones are noted for their irregularity in composition, as regards both the size of the individual grains of sand and also the material which cements the grains together. It is obvious that any fluid will move more rapidly through a coarse conglomerate imperfectly cemented than through a dense, fine-grained sandstone the particles of which are thoroughly coated and all the interstices filled with impervious cement. If the oil-bearing rock contains areas practically impervious, these areas, according to their size and position, will be more or less perfect barriers against the movement of the oil or the gas."

To this theory some objections were later raised by Munn[2] on the basis of observations in the oil pools of the Sewickley quadrangle, Pennsylvania. It was found that there was "no perceptible difference in the ratio of water to oil in the pay streaks at the top and bottom of the sand," and that "a lower pay streak may frequently be found to furnish a greater per cent. of oil to water than another located above." It was also found in one case that in a portion of the sand the salt water gained headway up the dip as the oil was exhausted through producing wells. So far this corresponded to the anticlinal theory. Down the dip of the same producing sand, however, a distance of less than three miles from these wells, this sand was found to be dry. To explain these and similar facts Munn developed

The Hydraulic Theory.[3]

This theory makes the accumulation of oil and gas dependent on moving water, water traveling through the rocks by hydraulic ("not hydrostatic") pressure and by capillarity, forcing the particles and small globules of oil before it, and allowing them to collect in pools where two or more such moving masses of water

[2] Malcolm J. Munn, "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," ECON. GEOL., Vol. IV., 1909, pp. 141–157.

[3] M. J. Munn, "The Anticlinal and Hydraulic Theories of Oil and Gas Accumulation," ECON. GEOL., Vol. IV., 1909, pp. 509–529.

conflict, or form an eddy. Capillarity is also thought to operate in segregating much oil into the more porous rocks. The accumulation and concentration process is looked upon as probably taking place subsequent to the desaturation of the original oil and gas-bearing beds. This process is described as occurring by means of the pressure of the overlying accumulating sediments while still on the sea bottom. According to the theory also, "the pools of oil and gas are held in place by water under hydraulic and capillary pressure, which effectively seals up all the pores of the surrounding rock and prevents the dissipation of pressure by diffusion."

Pressure in pools is maintained by the expansive force exerted by gas, which was either accumulated with the oil or generated subsequent to the formation of the pools. Such gas could not diffuse because of the saturated condition of the surrounding rocks.

To the exceptional structure in the Sewickley quadrangle, upon which this theory is based, Clapp[4] shows that the evidence when broadly considered is not "decidedly against the idea that the pools could have been accumulated by difference in gravity of oil and salt water."

Whatever may be the local effects of water acting in a purely hydraulic manner, such action is subordinate to the general hydrostatic flow of underground water, which moves from topographically higher intakes, to points of lower elevation, or to issue as springs lower down.

The Theory of Capillary Concentration.

This has been proposed by Washburne[5] as a general explanation of oil accumulation, with especial reference to one widely observed fact, namely the occurrence of oil in the more porous parts of a sand reservoir, in preference to other portions.

He points out the relative surface tensions of water and oil, which are about 75 and 25 dynes per centimeter respectively, or

[4] Frederick G. Clapp, Discussion of Mr. Munn's theory, ECON. GEOL., Vol. IV., 1909, pp. 565–570.

[5] Chester W. Washburne, "The Capillary Concentration of Gas and Oil," *Trans. A. I. M. E.*, Vol. 50, 1914, pp. 829–842. Discussion, 842–858.

as 3 to 1. Capillary openings range from .508 mm. diameter for tubular ones, down to .0002 mm.; and for sheet spaces from those with a width of .254 mm. down to as small as .0001 mm.

Within this range capillary action operates, and since its power increases as the surface tension and inversely as the size of the opening, water would enter the rock pores of the smallest dimensions, in advance of, and displacing oil, which would be forced into the remaining coarser spaces.

A working hypothesis in partial harmony with the anticlinal theory is suggested by Washburne along these lines: Gas would seek the highest points of arches and domes through its great mobility and low specific gravity. Oil would collect for the most part in the coarser openings by capillary action, and thereafter masses of it would often be carried by rising water up to a point beneath the gas or to the water-gas surface, where it would thereafter be held by surface tension. Some oil would also probably be carried up by gas as envelopes of bubbles, and come to rest at the water-gas surface, collected and held together by surface tension.

The Theory of Selective Segregation and Gravitational Separation.

Johnson and Huntley[6] have explained oil movement as due to "selective segregation" brought about by capillarity, immiscibility, and relative viscosity of oil, gas, and water. The agency of gravity is considered active only when not subject to capillary interference, and when movement takes place.

The efficacy of the latter factor is probably very great, and so far as observed by the writer this statement is generally admitted. It not only appeals as being reasonable, but has been demonstrated experimentally by Washburne and others. In the writer's opinion either crustal movement or movement of water in the rocks would tend to counteract the retention of oil in coarser capillary spaces after a certain quantity had accumulated. The oil would then likely be carried upward to the water-gas surface.

[6] Roswell H. Johnson and L. G. Huntley, "Principles of Oil and Gas Production," first edition, 1916, pp. 48–49.

The Filtration Theory.

Dr. Day and others found that when clay or fuller's earth is allowed to take up oil, fractionation occurs, and the oil driven out later when the clay is treated with water, is not the same as the oil which was first taken up by the clay. It was found that the oil removed had a much lower percentage of unsaturated hydrocarbons.

On these findings the theory is suggested that in those fields where the oil has traversed dry clays and shales in reaching its final "pool," or place of accumulation, considerable alteration by fractionation must have occurred. This would be one explanation of why oil varies so, sometimes in short distances.

OPENINGS IN ROCKS.

The hydraulic and capillary theories indicate that an overemphasis has been placed on rock pores and openings of capillary size, thus making the movement of oil dependent on the movement of water and on differences in surface tension, with a very small rôle to be played by gravity.

To understand openings in rocks, and their relative sizes, it is advisable to consider, not only as interstitial spaces, but also from a broader view taking into consideration the effects of diastrophic movements, stratigraphic relationships, and the incomplete cementation of sedimentary beds.

The question of rock openings has been most thoroughly treated by economic geologists, and the following table was arranged after assembling all known and possible openings in sedimentary rocks, of whatever cause or size, which are referred to in the writings of Van Hise,[7] Lindgren,[8] and Irving.[9] These were supplemented by others as hereinafter explained.

[7] Chas. R. Van Hise, "Some Principles Controlling the Deposition of Ores," *Trans. A. I. M. E.*, Vol. 30, 1900, pp. 38–39.

[8] Waldemar Lindgren, "Mineral Deposits," first edition, 1913, Chap. 10.

[9] J. D. Irving, Lectures in Economic Geology, Sheffield Scientific School, Yale University.

OPENINGS IN SEDIMENTARY ROCKS.

Super-capillary (>.508 – .754 Mm.).	Capillary (<.508 – .254 Mm.).
Original.	
(1) Drying cracks (mud cracked rock beds).	(1) Drying cracks.
(2) Rock pores (conglomerates, some limestones).	(2) Rock pores (sandstones, shales, limestones).
(3) Shell cavities (some shell limestones).	(3) ——
(4) Dolomite cavities.	(4) Dolomite pores.
Induced.	
(1) Due to folding (fissures, radial cracks, bedding partings, synclinal slumping).	(1) Due to folding (fissure openings, radial cracks, bedding partings, synclinal slumping).
(2) Compressional brecciation and conjugate fissures.	(2) Compression brecciation and conjugate fissures.
(3) Dolomitization, cavities.	(3) Dolomitization pores.
(4) Fissuring and rupturing apart from folding (joints, fissures by torsional stress).	(4) Rupturing apart from folding (joints and small torsional fissures).
(5) Solution cavities in limestone, dolomite, gypsum, and salt. With these belong also	(5) ——
(6) Fossil cavities dissolved out.	(6) ——
(7) Effects of former surface weathering below unconformities.	(7) Effects of former surface weathering below unconformities.

DISCUSSION OF TABLE.

(*a*) *General Statement.*

The openings listed above are divided into original and induced on the basis of cause, and into capillary and supercapillary on the basis of size. Subcapillary openings are omitted because they do not serve as channels of underground movement of either water or oil. The dimensions for capillary openings are those quoted by Van Hise and others. The table is largely self-explanatory, but some of the openings should be called to the reader's attention. All the known possible openings are listed but a few may be eliminated because experience does not indicate that they are generally developed. These will be referred to in their proper

order. Some openings are placed only in the supercapillary list because that is their characteristic development. This does not deny the possible existence in isolated cases of related openings which attain to only capillary size.

(*b*) *Original Openings.*

Drying cracks are usually entirely refilled, hence in practice would not often be found to exist.

The rock pores of some conglomerates are exceedingly coarse and may be supercapillary. In the case of limestones such as those of "Corniferous" age in the Irvine, Kentucky oil field, the writer has samples ranging from very dense close-grained rock, to spongy, open, cellular rock whose pores are clearly supercapillary, and form connecting spaces of considerable volume (see Plates XXIII., *A* and XXII., *D*).

Conspicuous openings of an original type are found also in some of the coquinas. These are referred to as No. 3 in the table.

(*c*) *Induced Openings.*

Under No. 1 of the later, or induced openings in rocks, those due to folding include a great number whose size and variety were first appreciated in the Wisconsin-Iowa-Illinois lead and zinc mines. These occur as important vein-filled channels cutting across the beds. There are also flat openings, or "flats," parallel to bedding planes and containing ore. Both types range in size from mere seams to several feet in width.

Radial cracks hardly appear in gentle folds, except as incipient openings. In close folds they may open and considerable disturbance result at crests and troughs because of their presence.

As pointed out by Lindgren,[10] large important openings may also occur at the tops of anticlinal arches by a parting and slipping along bedding planes, and are most important in the case of rock beds of unequal resistance. This class of openings may merge into capillary-sized spaces, but their development is generally larger.

[10] *Op. cit.*, p. 135.

Openings caused by compression, crushing, and the development of conjugate and complex fissure systems are deemed of great importance, and deserve especial mention in cases where they have developed fracture zones and belts of mashing.

Dolomitization cavities are important in many rocks as in the Trenton limestone, and in the dolomitic lenses which form the oil horizon for certain of the coastal dome pools.

Such openings are listed in all four parts of the table. This is done advisedly because of the latest research on the question of dolomitization, also because even the recent views are not yet harmonized. Thus some paleontologists find clear evidence that dolomitic replacement and alteration go on while deposition is in progress. Schuchert[11] favors the opinion that this has occurred in many cases where widespread dolomites occur, and that by diagenetic changes a porous dolomite has resulted. In such instances dolomite pores and cavities cannot be called induced, or subsequent openings.

On the other hand the openings of some dolomites are best explained as resulting from atmospheric leaching long after their formation,[12] and both this type of vesicularity and shrinkage due to replacement of lime by magnesia may result in producing openings. Thus dolomitic cavities are to be variously explained and appear to belong to both original and induced openings.

Fracturing, and rupturing apart from folding, may produce communicating channels of great extent in sedimentary strata. If they occur as joints they are frequently no larger than capillary openings, but where faulting has taken place they may assume dimensions of strictly supercapillary importance. The same is true where fissures develop caused by torsional stresses, and, due to tension, these may open to considerable width.

There also occur in limestones, dolomites, gypsum, and salt bodies solution cavities, which occasionally assume dimensions of extraordinary size. In so far as solution can be effective, all cavities, in rocks of whatever kind, may be enlarged, and the

[11] Chas. Schuchert, personal communication.

[12] Francis M. Van Tuyl, "New Points on the Origin of Dolomite," *Amer. Jour. of Sc.*, Vol.. XLII., 1916, p. 256.

action of underground circulation may thus contribute in giving to many originally capillary openings a supercapillary size.

Item numbered 6, fossil cavities dissolved out, will be seen to be of considerable importance in the Mexican oil reservoirs.

The final class of openings, surface weathering below unconformities, is one not referred to in literature on rock openings as such. They are concerned with observations in stratigraphy rather than economic geology, and the writer is indebted to Schuchert[13] for having his attention called to them.

Where formations occur bounded above by surfaces of unconformity or disconformity, they are often found to be exceedingly open and porous. Their porosity is ascribed in large part to the rotting, weathering, and general disintegration processes which they suffered during the interval of erosion when they were exposed as a land surface. While resubmergence was doubtless accompanied by saturation and partial closure by recementation and infiltration of matter, it is thought that much of their present porosity is due to the effects of the disintegration formerly suffered.

(*d*) *Conclusions from the Table.*

The table thus gives a better conception of the different classes of openings through which underground waters or other liquids circulate.

As Van Hise[14] has pointed out, all movement of a capillary nature is exceedingly slow, while through supercapillary openings it follows the ordinary laws of hydrostatics. Lindgren[15] modifies this slightly by saying it "is subject to a certain retardation on account of friction." Furthermore, the supercapillaries are not confined to any one bed, but may connect a series of beds vertically and laterally (the latter by bedding partings which form important channels for sidewise circulation, and for connecting vertical openings which offset one another). They are thus the trunk channels, and the capillary openings of all kinds, whether

[13] Chas. Schuchert, personal communication.
[14] *Op. cit.*, p. 41.
[15] *Op. cit.*, p. 32.

as original pores or as induced joint spaces, perform their function as subsidiaries to the main channels. The practical recognition of this is seen in those oil fields where the "shooting" of wells with nitroglycerine is carried on. In many wells the oil "sand" is encountered at places lacking the trunk channels, and oil seeps into the hole very slowly through capillary pores. By "shooting," trunk channels are induced which radiate from the well-bore in all directions, connect with other channels, and thus divert a large flow to the well.

To determine more closely the special forms of openings peculiar to the several kinds of oil horizons, and thus to enable the practical application of the discussion to be readily pointed out, it is advisable to subdivide the table of rock openings on the basis of the classes of oil horizons. Each of these classes may then be considered separately, with all the geologic factors which have contributed to its present state as a porous oil reservoir. This method also makes it possible to credit with proper importance the reservoirs other than sandstones, as the latter have been given a position perhaps more prominent than they deserve.

OPENINGS IN SANDSTONES.

Super-capillary (> .508 – .254 Mm.).	Capillary (< .508 – .354 Mm.).
Original.	
Induced.	
(1) Due to folding (fissures, bedding partings, synclinal slumping).	(1) Rock pores (interstitial spaces).
(2) Compressional brecciation and conjugate fissures.	
(3) Fissuring and rupturing apart from folding (joints and fissures by torsional and tangential stresses).	
(4) Solution cavities in calcareous sandstones(?).	
(5) Effects of former surface weathering below unconformities.	

[16] Questionable openings referred to in the general table are omitted in this and the following tables.

DISCUSSION OF TABLE.

In the general table on page 442 the original openings include fossil cavities. While these may occur sparingly in sandstones, they are too unimportant for mention. The spaces between sand grains are thus the most important original pores, and, except in some coarse conglomerates, are of capillary size.

Of the induced openings, the magnitude will depend upon the following factors: First, upon the amount of deformative strain the region has suffered; second, upon the thickness of the sandstone beds, and their relation to, and the character of, the intervening strata, that is, whether the latter may transmit a fracture or opening into underlying or overlying sandstones, or whether they are merely soft shales which quickly absorb the forces affecting the harder rocks. Finally the size of openings induced will depend upon the resistance offered by the sandstones themselves, a factor governed by the strength and nature of the cementing matrix. If the latter is weak or scarce, the sandstone is only a loosely consolidated sand which yields to movement by crushing. If strongly cemented, the sandstone will yield by broader folding, or be definitely fractured, jointed, or broken. If partially cemented, or only in certain areas, intermediate results will follow.

In the first case, obviously interstitial spaces represent the dominant form of porosity. In the second case, the interstitial space may become almost negligible, and cracks, joints, and fissures become the dominant form of porosity. In the third case a combination of original and induced porosity results.

The presence of all these factors of lithology, deformation, and stratigraphy, all variables, makes it evident that the pore space effective in controlling the movement and accumulation of petroleum, becomes a question of considerable perplexity. This suggests the futility of seeking accurate estimates of future production based upon determinations of the average per cent. porosity (original) in well samples from a partially explored oil sand. It is obvious also that pore space derived from samples of an oil sand give no clue whatsoever as to how much open space exists in the parent rock in the form of induced openings.

While inaccurate, such investigations of future production may be of some value in aiding the "feeling out" process in developing a field, for the purpose of ascertaining as far as possible the several factors which contribute to its porosity.

TYPES ILLUSTRATIVE OF THE VARIOUS CLASSES OF POROSITY.[17]

(*a*) *Original Openings.*

A sample of the Hoing sand, the productive horizon of the western oil fields of Illinois, may be considered typical of this class. This sand, from the Colmar field, is a light brown, rather fine-grained, porous, quartz sandstone with an indistinguishable cement. The grains are in part sharp, and it appears open textured in the hand specimen, yet does not crumble readily. Its open nature would give it chiefly an original, or interstitial porosity (see Plate XXII., *A*).

Similarly, a specimen from Red Fork, Oklahoma, from the Taneha sand of Pennsylvanian age, is made up of clean, light-colored, fine-grained quartz very poorly cemented. As a result the rock can be crumbled with ease between the fingers.

Of a similar character is the oil sandstone from the "Tiger Flats."

The most friable Oklahoma specimen, however, is one from the Cushing field, a pale tan sandstone, made up principally of sharp or subangular grains of quartz with a slight admixture of arkosic material, and some scattered fragments of calcite. A photograph of some of the sand grains rubbed from this fragile rock appears in Plate XXII., *C*, while *B* is a photograph of the specimen itself.

A still more friable specimen comes from the Santa Maria, California field. It is a fine-grained arkose, though not uniform, and shows in thin section a number of considerably altered feld-

[17] In the description of rock types the writer makes use of specimens secured from widely scattered sources. Especial attention has been paid to the descriptive data accompanying each sample, and of those submitted here and in later portions of the paper, it is felt that their origin and genuineness is unquestioned. The validity of the data is therefore to be accepted, and the material can properly be presented for study.

spars. Quartz is present in grains of all sizes within the textural range of the rock.

In this class of loosely consolidated sands, tests of interstitial porosity should give the closest approximations as to saturation of sands. Yet in California, where this type of reservoir predominates, the results of such tests have not always been satisfactory. Pepperburg[18] cites instances where, by carefully following rules worked out by the geological survey for estimating the probable oil contained in an undrilled, undeveloped district, one is very much disappointed in the results obtained. In one case where 60,000 barrels per acre were expected, production proved to be 250,000 barrels per acre. In others, where the estimate was 100,00 barrels per acre, production data extending over several months and even years, proved far short of this amount.

The collection of rocks from which the foregoing samples have been selected and described were gathered by the writer largely for the purpose of making quantitative porosity tests. But when the problem was analyzed it became evident that such investigations could not yield dependable results, and the best that can be done seems to be to outline the factors involved as has been attempted.

(*b*) *Openings Chiefly Induced.*

The writer's collection includes a piece of Berea sandstone from the Corning oil "pool" of Perry County, Ohio, which was shot from a well at a depth of 1120 feet. This rock in the hand specimen is a dense, even-grained, very uniform, nearly white sandstone. Viewed in thin section, it is an aggregate of pure quartz grains set in a solid matrix of calcite. Estimated by the eye alone, the calcareous cement occupies about 50 per cent. of the area of the section. The quartz grains are sharp to subangular, and the rock appears to be so closely cemented that it is difficult to see how either water or oil could penetrate. The grip which the cementing bond of calcite has upon this rock, and the thoroughness of its penetration and interfilling is forcibly brought to attention by the way whole areas extinguish at once between

[18] Leon J. Pepperburg, communication to the writer.

crossed nicols. This indicates a strong tendency to crystallize in large crystals in spite of the presence of the quartz grains. It is difficult to see how oil in commercial quantities could be stored in such a rock, or if present, how it would yield itself fast enough upon being tapped to furnish a paying supply, because such a capillary flow would be very slow. In those "pools" of Ohio where rich strikes have been encountered in this rock it must either have had a much weaker binder, as Bownocker[19] claims generally for it, or the porosity would have to be looked for largely in the openings readily induced by any stress tending to deform so rigid a rock. These would be prominently developed at the crests of folded areas and would provide upward passages from the bituminous shales which underlie it, and are looked upon as the beds of origin.

Another sample, from the Bald Hill "pool" of Oklahoma, is tight and well cemented. It consists of a fine-grained aggregate of quartz grains, not very sharp, and interlocking in exceptionally close contact throughout. In such a reservoir one should expect to find an appreciable percentage of the effective porosity in joints, cracks, and other induced openings. Such seems to have been the case as Hutchison[20] found that the limited surface structure in the Bald Hill-Morris district indicated close crumpling and mashing. The somewhat erratic nature of production ascribed to the district lends support to the same conclusion.

Several samples secured from districts in southern California are very close, tight rocks. They are from oil-bearing horizons, and while unusual because of the generally loose and unconsolidated character of the California oil sands, they are said to be representative of the strata from which they come.

One of these is a medium-grained, dense arkose-conglomerate from the Fullerton oil fields.

A second from the Salt Lake field has fine quartz grains

[19] J. A. Bownocker, "Oil and Gas," Geol. Survey of Ohio, Bull. 1, 4th ser., 1903, p. 22.

[20] L. L. Hutchison, "Preliminary Rept. on the Rock Asphalt, Asphaltite, Petroleum, and Natural Gas in Oklahoma," Okla. Geol. Survey Bull. No. 2, 1911, pp. 216–220.

cemented with calcite, the whole containing larger darker masses of some hard much altered unrecognized material.

A third from the Maricopa field is chiefly arkosic and the grains are bedded in a calcareous cement.

A fourth is very fine-grained and not so closely cemented. It is a gas sand from the Midway fields and consists of an arkose with a matrix of calcite.

The density of these rocks precludes that porosity restricted to original interstitial spaces would yield a big production, especially in the heavy oils of California. The development of complex structures undergone by the rocks of this region would produce in such hard strata numerous induced openings. To such again it seems not unreasonable to look for an important source of their porosity.

(*c*) *Original and Induced Openings.*

There remain for consideration the intermediate types of sandstones which arise from poorly assorted sediments, such as argillaceous sandstones, or those in which the cementing bond is so variable in amount and character that no similarity exists in the samples from well to well of the same "pool." In this class also may be placed for convenience such rocks which may be pure, but are neither rigid nor unconsolidated.

The argillaceous type appears to be represented by one small sample from the Lander, Wyoming, field. It is made up of very fine grains of quartz, some calcite, and a large proportion of clay. It is friable enough to be placed in the class of loosely consolidated rocks, but the presence of so much clay would be likely to render it impervious in some parts of the "pool," hence variable in its oil content. In the same class belongs the "Booch sand" from the Bald Hill-Morris district in Oklahoma, whose microscopic character and shreds of gray shale visible to the naked eye indicate it is a rather impure sandstone.

The rocks of variable cementing bond are well illustrated by specimens shot from the sandstone reservoir of the Broken Arrow, Oklahoma field, which appear to be hard but can be rather easily broken by hand. In color they are a clean light yellow. In

thin section some areas are merely a closely packed series of half-rounded and subangular grains of quartz, while in others the interstitial spaces are filled with calcite. The same type of variably cemented rock, but in a less pure sandstone, is illustrated by a specimen from the eastern edge of the Bird Creek, Oklahoma, "pool," in the salt water area. This sample is from the Bartlesville sand.

Rocks of the intermediate type may be illustrated by one from the Muskogee oil sand, of basal Pennsylvanian age, and of a clear grayish-white color. Examined in thin section, it is seen to consist of fine and very fine quartz grains, closely spaced, or otherwise.

The individual samples of all three classes mentioned above are merely illustrative, and determinations made for any field should include as many samples as possible in order to obtain representative results.

OPENINGS IN LIMESTONES AND DOLOMITES.[21]

Original.

Super-capillary (>.508 — .254 Mm.).	Capillary (>.508 — .254 Mm.).
(1) Rock pores in limestone and dolomite.	(3) Dolomitization pores.
(2) Fossil cavities in shell limestone or coquina.	(5) ——
(3) Dolomite cavities.	(6) ——
(2) ——	

Induced.

(1) Due to folding (fissures, bedding partings, synclinal slumping).
(2) Compressional brecciation and conjugate fissures.
(3) Dolomitization cavities.
(4) Fissuring and rupturing apart from folding (joints, fissures by torsional stress).
(5) Solution cavities in limestone and dolomite, including,
(6) Fossil cavities dissolved out.
(7) Effects of former surface weathering below unconformities.

[21] This table contains a list of those openings selected from the general table on page 442 which are peculiar to limestones and dolomites.

DISCUSSION OF TABLE.

Since limestones, magnesian limestones, and dolomites are essentially rigid rocks, it follows that the classification of their pores is not dependent, to the same extent as in sandstones, upon a varying degree of resistance offered to deformative stress.

Where dolomitic reservoirs are treated in the following discussion, no attempt is made to classify that part of their porosity due to dolomitization as induced or original, because the criteria are not at hand to determine which it is.

ILLUSTRATIVE TYPES.

(*a*) *Openings, Original and Induced.*

Munn[22] found the Beaver Creek oil "sand," in Wayne County, Kentucky, to contain important natural pores between interlocking calcite crystals, and this rock serves as one example of the first class of oil-bearing limestones. It is illustrated in Plate XXII., *D*. For want of more data it is assumed by the writer that this porosity is the dominant variety. As the rock, however, is described to be a "cherty geode-bearing limestone," it seems not unlikely that openings induced by former traveling solutions and secretionary processes may contribute to the original pore space. Finally openings probably exist induced by folding, and in joints.

Other specimens from Kentucky are shown in Plate XXIII., *A*, which constitute the Irvine oil "sand," of the Irvine field in Estill county.

The porosity of these pieces, as well as that of the Beaver Creek, is noticeably variable, and in the case of the Irvine field, Glenn[23] states that the wells which strike the "loose sand" rarely require shooting, while those in the "tight sand" do.

A type probably containing much more effective original porosity than either of the preceding limestones, is the McCloskey "sand" from the upper part of the Ste. Genevieve (Upper Mississippian) formation in Illinois (see Plate XXIII., *B*). It is

[22] M. J. Munn, "Reconnaissance of Oil and Gas Fields in Wayne and McCreary Counties, Kentucky," Bull. U. S. G. S. No. 579, 1914, pl. 2.

[23] L. C. Glenn, communication to the writer.

friable, open-textured and oölitic, qualities which are not always characteristic of the formation from which it comes, but which lend enormous storage capacity where they are present. The thin section reveals a cement of calcite sparingly present between certain of the spherulitic grains. This scarcity of cementing bond explains its open, friable quality.

The rock from the McCloskey at the north end of the main oil field in Clark County, however, is not an oölite, but a dolomitic limestone. This is seen from Plate XXIII., *C*, to contain numerous good-sized openings.

(*b*) *Openings Induced.*

Fissures in limestones are included in the table on page 442. From such openings comes the oil in the fields of Tennessee and a part of southern Kentucky as reported by Purdue.[24]

Under this subdivision of induced openings belong also two of the most important limestone oil fields of North America. These are the Trenton limestone fields of Ohio and Indiana, and the oil fields of Mexico. The high percentage of induced porosity to which their prolific nature is, or has been, due, consists mainly of two kinds: (*a*) For the Trenton fields, openings attributed to dolomitization combined with those related to folding, fissuring, and jointing, with the latter in some cases enlarged by solution and possibly other causes. (*b*) For the Mexican fields, openings caused primarily by fissuring, possibly enlarged by solution, accompanied by important minor openings in the form of dissolved-out fossil cavities. The fields will be treated in the order named.

THE TRENTON LIMESTONE FIELDS.

Orton[25] called attention to the fact that oil in this formation is found where two conditions are met, namely (*a*) in structurally favorable areas where (*b*) dolomitic replacement of the

[24] A. H. Purdue, state geologist of Tennessee, personal communication to the writer.

[25] Edward Orton, "The Trenton Limestone as a Source of Petroleum and Natural Gas in Ohio and Indiana," 8th An. Rept. U. S. G. S., Pt. 2, 1886–1887, p. 662.

limestone has occurred. In Plate XXIV., a specimen of Trenton from Ohio is illustrated. This rock appears to be more or less magnesium throughout, and in the large openings occur rhombohedral crystals of dolomite, which part from the walls smoothly. This points to their introduction subsequent to the formation of the cavities. These, then, are not dolomitization cavities due to a shrinkage of volume accompanying the replacement of lime by magnesia. Orton[26] has pictured the microscopic structure of the Trenton in which openings attributed to such action are shown. It seems possible also that some of the openings shown in Plate XXIV., have resulted from the enlargement by solution of original genuine dolomitization cavities. It is also of interest to observe that most of the openings show a rough alignment, or are confined to a well-defined zone, as if they were the result of solution by waters traveling along a seam, joint, or bedding plane. This fact strongly suggests the presence generally throughout the limestone of enlarged open spaces along induced joints and cracks.

Another feature of this specimen of Trenton is the smooth rounded surface of the whole mass. It has been suggested that abrasion by gas, or "gas erosion," may be the cause, and if such action occurred as an accompaniment of oil and gas accumulation in the Trenton, it would be a factor contributing toward porosity. Whether oil has any solvent power to create a reservoir for itself as it enters a formation is not known, although the writer has encountered the suggestion several times.

The fact that the Trenton dolomite has yielded most of its oil from the upper portion, and that there is an unconformity between its surface and the overlying Utica shale, suggests that a part of the porosity of this field may have arisen from conditions due to weathering in the land interval before the deposition of the Utica.

THE RESERVOIR ROCKS OF THE OIL FIELDS OF MEXICO.

The oil is found in a zone extending from near the top of the Tamosopo (Cretaceous) limestone into the basal portions of the

[26] *Op. cit.*, pl. 60, opposite p. 644.

overlying San Felipe (Upper Cretaceous) beds of alternating limestone and shale. So far as experience goes it does not occur far down in the 3,000 feet or more of massive limestones underlying the San Felipe. The upper limits are effectually set where the limestones of the alternating series rapidly thin and give way to thicker and softer, hence impervious, shales. The latter extend upward through an unbroken thickness of from 1,500 to 4,000 feet, making the heavy shale cap, and appear in a good part of the oil belt as the surface formation.

Where observed at the outcrop, the Tamosopo is a heavy-bedded, gray, coarsely crystalline limestone (see Plate XXVI., *A*). Plate XXIII., *D*, is the photograph of a small piece blown from the Cortez Oil Corporation's well in the hacienda of Tepetate. The vug in the upper part of the front face is a druse studded with tiny crystals of calcite. When first sawed in two a strong odor of gas issued. In the right hand piece of the enlarged view (Plate XXV., *A*) small specks of oil are shown. These issued from tiny cavities as soon as the latter were exposed by sawing. Others are distributed throughout the rock, as was discovered upon destroying one of the halves of this piece. All contained heavy black oil which issued under a slight pressure. Larger holes are present also, some on the outside of this and other pieces blown from the same well. A few are large enough to admit the large end of a lead pencil. So far as seen by the writer they range from this size down to tiny pin holes.

The well from which this rock came is one mile north of Juan Casiano, the prolific camp of the Huasteca Petroleum Co. (Doheny interests). It is probable therefore that the reservoir rock from which the immense production of Juan Casiano well No. 7 has come is of a similar nature. That the Tamosopo has this porosity over an even wider range is proved by pieces blown from Potrero No. 4, the famous gusher of the Mexican Eagle Oil Co. at their Potrero del Llano camp, twenty-five or thirty miles farther south. The nature of this rock is shown by the photograph, Plate XXVIII., *A*. Whatever the extent of these openings, there is no question of their greatly adding to the storage

capacity, and hence as one form of effective porosity, it is of interest to inquire into their origin.

So far as known, dolomitization has played no part in these openings. Analyses[27] of samples from Dos Bocas, Potrero del Llano, Alazan, and Naranjos in no case show more than 2 per cent. of magnesium carbonate. Salt waters from the wells of some of these camps have also been analyzed and show only a trace of magnesium salts.

In thin section, the rock from the Cortez well is seen to be made up of an innumerable quantity of fossil remnants of all sizes, having a rather coarsely crystalline texture. They are embedded in an extremely fine-grained, cryptocrystalline to amorphous calcareous cement, doubtless derived as a lime mud, or paste, from the constant agitation of the shells by wave action in a shallow sea.[28] One section of this rock, ground from a portion having both large and small pores, reveals that the more coarsely crystalline calcite of the fossils is dissolved out. Various stages can be seen, from those in which only the central portion is gone, to others revealing a whole cavity conforming with the outline of the original fossil.[29] These several features are portrayed by the micro-photographs in figures *B, C, D,* Plate XXVI.

Porosity, in the nature of small capillary and supercapillary openings, is also present in at least one locality in the San Felipe limestones of the alternating series overlying the Tamosopo. One view of the basal portion of this series, showing essentially only limestones, may be seen in an outcrop in the Sierra de Tamaulipas about 100 miles north of Tampico (Plate XXVII., *A*).

Its appearance in well samples is illustrated by several pieces blown from Waters-Pierce[30] well No. 5 in the Topila field. Some of these are unaltered limestone as the one in Plate XXV., *B*. Others have been rendered cellular and porous, and are partially

[27] Information furnished by the courtesy of E. L. DeGolyer, chief geologist for the Mexican Eagle Oil Co.

[28] This explanation is suggested to the writer by Professor Chas. Schuchert.

[29] This explanation of cavities in the Tamosopo was formerly suggested to the writer by Mr. John M. Muir, geologist of the Corona Oil Co., Tampico, who thought their shape indicated such an origin.

[30] Now the Pierce Oil Corporation.

silicified. A piece of the latter is shown in Plate XXVII., *B*. The cellular rock is seen to have a banded arrangement, and this is parallel to the chert. The chert may become much thicker and is widely noted in the drillings. Sometimes it is present in nodular lenses as indicated by the piece in Plate XXVII., *C*.

The foregoing rocks are of interest when studied in thin section, first for their composition, and second for the evidence they furnish leading to the explanation of the cellular, banded porosity. They are all made up of myriads of foraminifera, mostly present in small round forms, but in one section consist chiefly of elongated lenticular shapes. These are bedded in a limy, argillaceous matrix. Often they are rather evenly distributed, but frequently are gathered in clusters and aggregates covering a considerable area. In some of the rocks they are of crystalline calcite—their normal composition—in others they have been largely replaced by opaline silica. In numerous cases mineral matter is lacking, and only a round or elongate hole appears in the section. In a few cases the holes were seen to be partially opened foraminiferal cavities, showing some of the peripheral circular outline remaining. A number of the larger holes have hour-glass shapes. Others are large and irregular, but with semi-circular parts in their boundaries. The holes are generally in a parallel arrangement similar to the foraminifera of some of the sections.

These facts rather clearly indicate the explanation for this banded, cellular porosity, namely a solution of the lime tests of the foraminifera with only partial replacement by silica. The large holes, which are often many times the size of the average foraminifera, may be explained by the solution of the local, densely packed portions of the rock. This is strongly suggested by their lobed outlines. The banded tubular openings correspond to the banded arrangement of the fossils.

A parallel arrangement of foraminifera was observed also in specimens from Mexican Oil Co. well No. 3, Topila field, and for Corona well No. 1, Panuco field. But these rocks show no porosity, and the foraminifera have their normal composition of calcite.

With the explanation of these fossil pores only a part of the

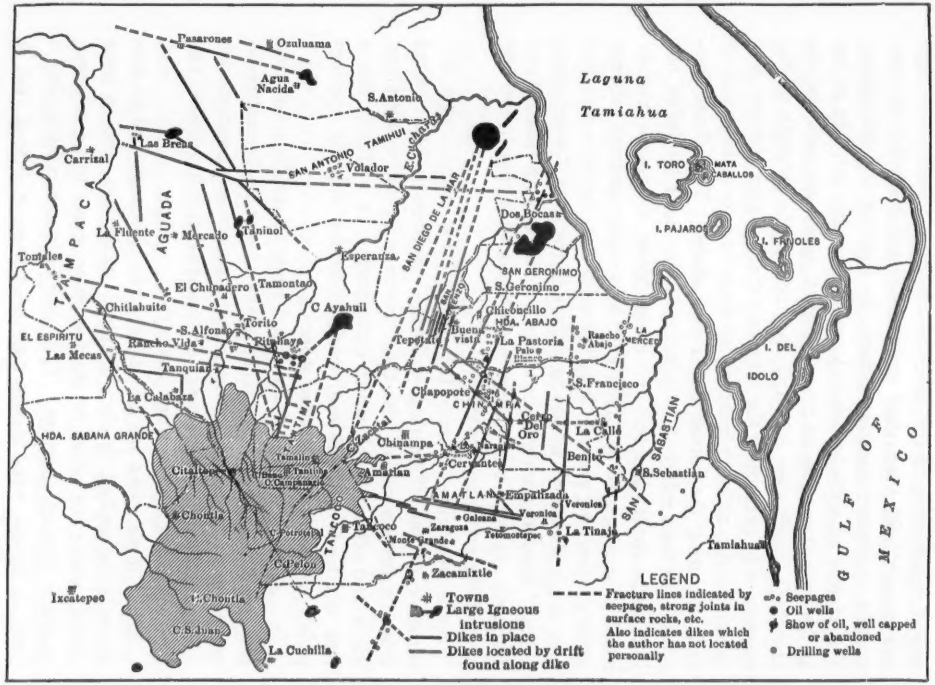


FIG. 17. Map of a part of the southern oil fields, Mexico. After Huntley.

effective porosity of the Mexican oil reservoirs has been mentioned. Reference to the table of limestone openings on page 452, coupled with the faulted structures found in Mexico, at once suggest important openings induced by faulting and fracturing. The history of wells and their location bear this out. In so far as the several systems of fractures exist which are indicated on Huntley's map[31] (see Fig. 17) they add to the strength of the suggestion by permitting the inference that complex stresses, perhaps torsional, aided in breaking up these limestones and jointing and fracturing the harder San Felipe shales. That these fractures have been enlarged by solution is also not improbable, nor is it to be overlooked that movement along a sinuous fracture surface, as suggested by Lindgren,[32] may cause openings between alternate touching points. It is not quite clear to the writer just how much Huntley[33] wishes to include in the term "water channeling," but it is presumed he means joints, bedding partings and fractures enlarged by solution in the sense indicated in the first part of the preceding sentence.

Some geologists express the opinion that considerable disturbance of the oil-bearing sediments of Mexico has resulted from causes associated with their intrusion by the many plugs, dikes, and sills of basalt which occur there. In so far as this is true it affords an additional explanation for induced openings which may contribute to pore space.

In conclusion it may be said that a study of the Mexican samples forcibly suggests an entrance of the oil into the present reservoir through the coarser openings, with subsequent impregnation of the surrounding finer pores. It appears that it has soaked into the rock bounding the trunk channels.

While these rocks are limestones, this view may just as consistently be applied to close textured sandstones, and to some shales, where the principal storage space seems to be in supercapillary induced openings. This view is in contradistinction to

[31] L. G. Huntley, "The Mexican Oil Fields," *Trans. A. I. M. E.*, Vol. 52, 1915, p. 310, Fig. 6.

[32] Waldemar Lindgren, "Mineral Deposits," first edition, 1914, p. 139.

[33] *Op. cit.*, pp. 305, 313, 314.

what seems to have been commonly held, that the oil is present mainly in interstitial pores with merely an exit through larger openings. It implies a *working into the country rock* throughout geologic time, rather than the reverse process of working outward from a position imprisoned in interstitial rock pores. The latter process probably obtains during movement *from* the beds of origin, while the former is characteristic of movement *into* the rocks of accumulation.

OPENINGS IN SHALES.

	Original.	
	Super-capillary (> .508 – .254 Mm.).	Capillary (< .508 – .254 Mm.).
	(2) ——	
	Induced.	
(1)	Due to folding (fissures, bedding partings, synclinal slumping).	(1) Drying cracks.
(2)	Compressional brecciation and conjugate fissures.	(2) Rock pores.
(3)	Fissuring and rupturing apart from folding (joints, fissures by torsional stress).	
(4)	Effects of former surface weathering below unconformities.	

DISCUSSION OF TABLE.

Shales become effective oil reservoirs only if hard enough to offer resistance to deformation, when they yield by folding and fracturing. In this sense only can the various classes of induced openings listed in the foregoing table develop. When very soft, on the contrary, deformation will simply mold the shales, leaving them close and impervious. Because of frequent tendency to develop thin beds, or closely spaced laminæ, many joints develop when these thin beds suffer deformation. It is probable that some joints also originate as drying cracks.

Whatever the several causes are, a considerable induced porosity may be developed in such hard shales, which can be effective for the storage of petroleum.

ILLUSTRATIVE TYPES.

The harder shales interbedded with the limestones to form the alternating, or San Felipe, series have been mentioned in the discussion of the Mexican fields. These are notably resistant where observed in the beds outcropping in and near the town of Valles, state of San Luis Potosi, 70 or 75 miles west of Tampico. That these shales form a part of the oil reservoir rocks is proved by many wells never reaching the top of the Tamosopo limestone, and by their being ejected from newly drilled gushers. Such specimens are illustrated in Plate XXV., *C*, and Plate XXVIII., *B* and *C*. All of these shales are dense, close, hard, and apparently dry. They are also very limy. Moistened with water, capillary action is noticeably slow. Hence they appear to fail entirely in taking up the more viscous, heavy, Mexican oil. The low surface tension of oils is also probably instrumental in keeping it out of these shales.

As further illustrating the occurrence of oil, wholly or in part, in broken shales on this continent, may be mentioned the oil fields of Florence, Colorado, Katalla and Cook Inlet, Alaska, and the Santa Maria field, California.

CONCLUSION.

A review of the preceding evidence reveals the enormous importance of induced porosity in oil accumulation. This applies to reservoir rocks of all three types, sandstones, limestones, and shales. It entirely overshadows the original porosity of an interstitial nature except in the case of loosely consolidated sands. This is true not alone because any one type of induced openings may afford large storage, but also because there are so many causes contributing toward induced porosity.

Thus there are openings first, due to folding, which manifest themselves as fissures and bedding partings; second, resulting from compressive stresses, producing brecciation, and sometimes complex and conjugate fissure systems; third, dolomitization cavities in altered limestones; fourth, fissures and rupturing of

rock beds from causes other than folding, from which result numerous joints and torsional breaks; fifth, important enlargement by solution of all the other types of porosity; sixth, cavities arising from the solution of fossil forms present in the rocks; and finally, a source of openings not before emphasized in the literature, if referred to at all, namely the effects of weathering agencies, percolating waters, chemical activity, and organic destruction which must have acted on every formation exposed to atmospheric agencies such as those now marked by unconformities at their upper terminations.

All discussions of porosity heretofore published have been of too limited a scope, and have erred in not sufficiently recognizing the part played by openings of an induced nature. They have furthermore gone to the extreme in this limited discussion of original porosity by attempting to find accurate percentages of voids based on the absorptive properties of oil rocks. It has been shown how wide of the mark such computations are, and how unreliable even in the case of loose sands where interstitial porosity is the dominant variety. A better method of estimating future production is the production curve, which is based on actual yields of oil and therefore must include the effect of *every* factor entering into production for the field tested.

Porosity tests have all gone back to the original King and Schlichter method of finding how much space is contained between sand grains, and this general scheme of computation has been followed and referred to in foreign journals. Thus it has happened that a porosity factor of often minor consideration has been dealt with alone, to the exclusion and disregard of all the other, often much more potent factors.

Recognizing porosity then from this broader viewpoint, it is easy to come to a conception of underground water circulation controlled by hydrostatic laws. If this be granted an important sidelight on oil accumulation is at hand, and the widespread induced openings serve not only a freer water movement, but also to reëstablish the anticlinal theory. When, in addition to this, it be remembered that the authors of other theories have not

wholly denied the important value of anticlinal accumulation, and seek to harmonize their new theories with it, it seems fairly conclusive that the conservative statement of the anticlinal theory quoted in the beginning of this paper should stand as established.

ACKNOWLEDGMENTS.

The writer is deeply indebted to the following sources for statistical data, rock specimens, and personal help in the preparation of this paper:

To his former colleague, Mr. John M. Muir, geologist for the Compania de Petroleo la Corona, Tampico, Mexico, and to the manager, Mr. C. Van Geytenbeek, and other representatives of that company, he is especially grateful for a large and representative suite of specimens from the reservoir rocks and associated strata in the Mexican oil fields. Mr. Muir has also been most kind in gathering statistical data and answering questions which came up in the course of writing.

To Mr. R. A. Conkling, head geologist of the Roxana Petroleum Co., and to Mr. James H. Gardner, consulting oil geologist, both of Tulsa, Oklahoma, sincere thanks are due for samples of sands from the oil horizons of the Mid Continent field.

Samples from Illinois were kindly furnished by the State Geological Survey; from Ohio by Mr. J. A. Bownocker, state geologist; and from Kentucky by Dr. L. C. Glenn, of Vanderbilt University, Nashville, Tenn. From the California fields, a suite representing both surface rocks and the oil reservoirs were supplied by Mr. W. W. Orcutt, geologist for the Union Oil Co., Los Angeles.

Some production data from these fields were added by Mr. Leon J. Pepperburg, consulting geologist, San Francisco; and data of occurrence of the oils in Tennessee and Kentucky are at hand from Mr. A. H. Purdue, director of the State Geological Survey of Tennessee.

Valuable data were received from the reports of the United States Geological Survey and from many other books and jour-

nals treating on petroleum. For these and to such other sources not herein specified, acknowledgment is cited in the footnotes.

Finally, it is the writer's great pleasure to mention the invaluable suggestions received, not only as to handling material, but also in criticism of manuscript, from the following professors of geology in Yale University: J. D. Irving, L. V. Pirsson, Charles Schuchert, Joseph Barrell, Wm. E. Ford, and Alan M. Bateman.

EXPLANATION OF PLATE XXII.

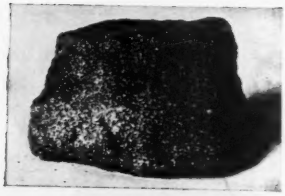
FIG. A. Hoing sand from Colmar field, McDonough county, Illinois. Natural size.

FIG. B. Sandstone from the producing horizon of a well in the Cushing field, Oklahoma. Natural size.

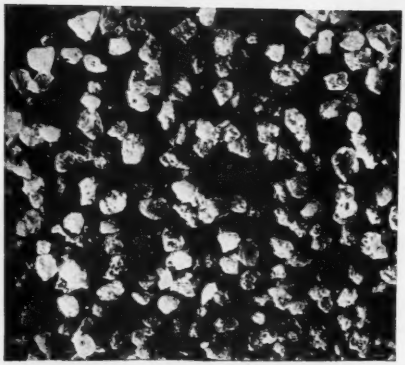
FIG. C. Grains of sand from the sandstone in Fig. B. Magnification 16 diameters.

FIG. D. Very porous oil-bearing limestone from Wayne county, Kentucky. Enlarged 2 diameters. After Munn.

A



B



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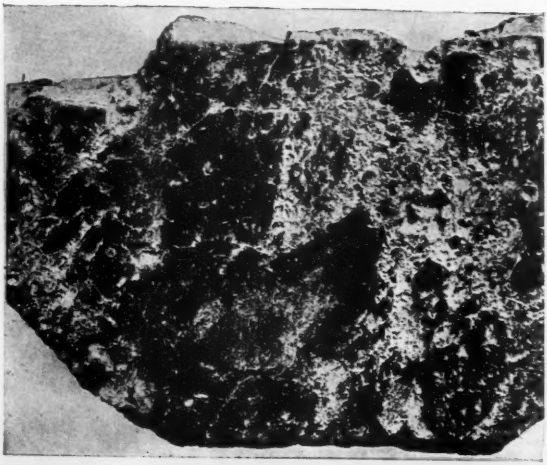

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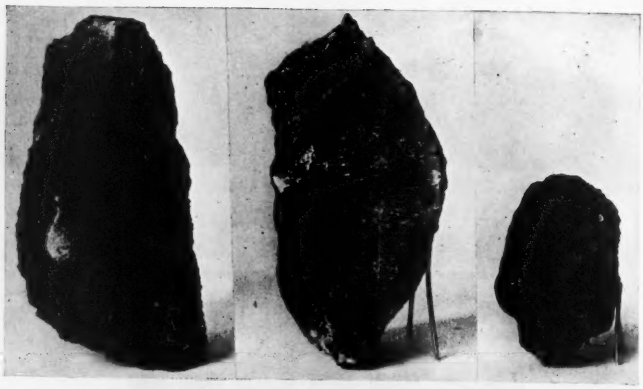
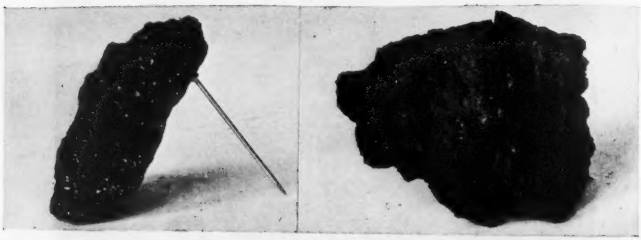


A

B



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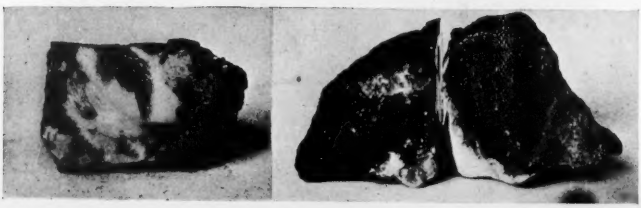


D

EXPLANATION OF PLATE XXIII.

FIG. A. Corniferous limestone from the Irvine, Kentucky, field. Left to right: First, porous specimens from outcrop in railroad cut, town of Irvine; second, less porous portion of same outcrop; third, piece of "tight" limestone shot from a well on Station Camp Creek, six miles S.S.E. of Irvine. Natural size.

FIG. B. McCloskey "sand" from a well in Lawrence county, Illinois. Right, piece sawn in two. Left, polished face of left hand portion. Natural size.

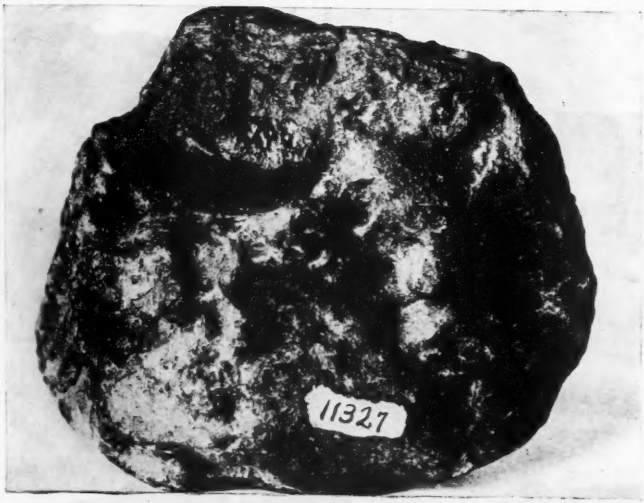
FIG. C. Specimen of dolomite from McCloskey "sand," Illinois. Left, polished face of one portion. Natural size.

FIG. D. A piece of Tamosopo limestone blown from well of Cortez Oil Corporation, hacienda of Tepetate. Natural size.

EXPLANATION OF PLATE XXIV.

FIG. A. A piece of Trenton limestone shot from a well near Findlay, Ohio, at a depth of 1,425 feet. Four fifths natural size.

FIG. B. Same piece as in preceding figure seen from reverse side. Four fifths natural size.



A

B

A

B

C

EXPLANATION OF PLATE XXV.

FIG. A. Enlarged view of pieces in Plate XXIII., Fig. D.

FIG. B. Specimen of San Felipe limestone blown from Waters-Pierce well No. 5, Topila field, Mexico. Natural size.

FIG. C. Specimen of San Felipe shale from well No. 2 of the Tal Vez Oil Co., Panuco field. Left hand sectional view reveals a complete lack of penetration by oil, although specimen was immersed in it.

EXPLANATION OF PLATE XXVI.

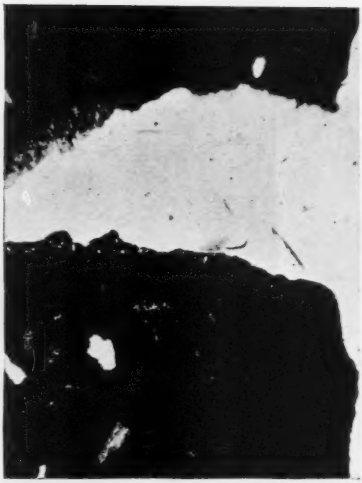
FIG. A. Tamosopo limestone in an upthrust block, Micos Canyon, on the railway from Tampico to San Luis Potosi.

FIG. B. Section of Tamosopo showing portion of its fossil structure. × 20 diameters.

FIG. C. Cavities caused by fossils dissolved out of Tamosopo limestone. × 20 diameters.

FIG. D. Same as above. Note fragments still remaining, undissolved, in some holes. × 20 diameters.

A



C

B

D

A

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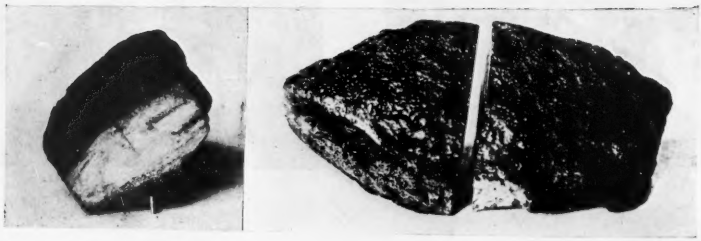


C

EXPLANATION OF PLATE XXVII.

FIG. A. San Felipe limestone outcrop in the Sierra de Tamaulipas, 100 miles north of Tampico.

FIG. B. San Felipe limestone blown from Waters-Pierce well No. 5, Topila field, Mexico. Light portion (left hand view) chert. Dark is oil-soaked cellular rock. Natural size.

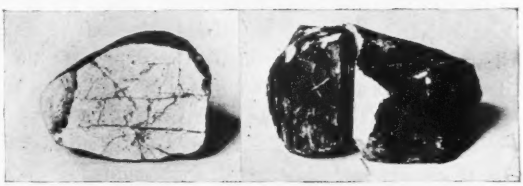
FIG. C. Cherty nodule blown from Waters-Pierce well No. 5. Left hand sectional view, white is cherty material and very hard; black is soft oil-soaked rock enclosing it above and below.

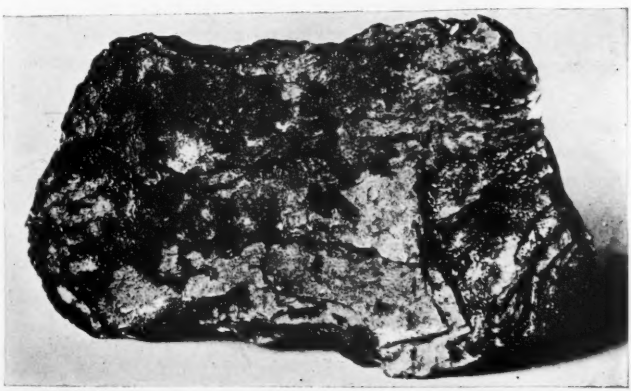
EXPLANATION OF PLATE XXVIII.

FIG. A. Specimen of Tamosopo limestone from well No. 4, Potrero del Llano. Copy of a photograph presented to the writer.

FIG. B. Specimen of shale blown from Harmon gusher, Panuco field. This is much harder than that shown in Pl. XXV., Fig. C. Sectional view shows total absence of penetration by oil.

FIG. C. Another specimen of shale from Harmon well. Where chipped below upper right-hand corner, the white spot shows clean interior.





MANGANESE IN THE DAKOTA SANDSTONE OF CENTRAL KANSAS.

W. A. Whitaker and W. H. Twenhofel.

Some time in 1914, the senior writer received from Raymond, Kansas, some material for examination, which the sender stated occurred on his farm in great quantities. An assay of the material showed about nine per cent. of manganese calculated to the metal. As nothing was known of the geological conditions of occurrence and since manganese in such percentages in the rocks of Kansas had not previously received published notice, a field investigation was made by the junior writer during the field season of 1915.[1]

Raymond is a small Santa Fe Railroad village in the southeastern corner of Rice County, which is approximately the central county of the state. The village is on the northern edge of the floodplain of the Arkansas River, whose alluvial deposits heavily cloak the surrounding lowlands. More or less broken-down cliffs of lower Dakota sandstone occur just east and north of the village and constitute the river edge of the Dakota upland stretching away to the north and east.

The T. C. Leming farm, from which the specimens came, lies on the uplands about three miles north and two miles east of Raymond. The soil of the farm is a sandy loam which appears to be quite fertile and, over most of the area examined, not of great thickness. It seems to have been produced through the weathering of the Dakota sandstone.

With the owner, Mr. T. C. Leming, the junior author examined the locality of the specimens. This, for the most part, consists of a flat, basin-like area at the head of a small valley. Similar specimens were found to be frequent on the surface and the owner

[1] The senior writer is responsible for the chemical analyses, the junior writer for the data which are related to the geology.

stated that bed rock of a similar character occurred in many places less than a foot beneath the surface where often it was scratched by tools during cultivation. He was not able, however, to locate such places; but it is nevertheless quite certain that such are present.

The specimens scattered on the surface are of a dark-brown to black color and quite friable and soft. They resemble partially weathered fragments of Dakota sandstone, but differ therefrom in being more friable, less porous and of a darker color. Since Dakota sandstone is known to underlie the region, it is probable that a local variety lies beneath the field.

The following is a representative analysis of the substance.

Moisture and volatile	4.24
SiO_2 and insoluble	71.75
Fe_2O_3	4.74
CaO	1.43
MgO	.80
SO_3	4.86
Mn_3O_4	12.08

The manganese appears to be present as "wad," *i. e.*, an impure mixture of manganese oxides.

The source of manganese is not known, but it is assumed to have been in the sandstone, whence it was probably concentrated through groundwater and perhaps bacterial action, in the basin-like area where it is found, through subtraction of substances other than manganese and enrichment of what remained through precipitation of manganese from solution. The water probably obtained it from the sandstones which underlie the higher fields surrounding the area. It is considered quite improbable that the manganese content will increase in the deeper lying strata.

In this connection it is interesting to note that at Hutchinson, Kansas, about thirty-five miles below Raymond on the flood plain of the same river, the city water mains have at times been stopped up by the formation of a deposit which is high in manganese.[2] The water is obtained from points driven into the sands and gravels of the Arkansas Valley. The deposits which form in the

[2] E. H. S. Bailey, *Jour. Am. Chem. Soc.*, Vol. 26, p. 714.

water mains, and which cannot be removed by flushing, are described as "an earthy brown color, porous, soft and friable." The analysis of a sample dried at 100° C. was given as follows:

Silica	9.25
Ferric oxide	13.00
Aluminum oxide	3.02
Manganese sesquioxide	45.20
Zinc oxide	5.94
Calcium oxide	.48
Copper oxide	.66
Barium oxide	.11
Water	7.59
Loss on ignition, less water	13.67
	98.92

The water at Hutchinson, at the time the above deposit was reported, contained only 0.0014 gram of manganese sesquioxide per liter.

Deposits somewhat similar to those at Hutchinson have been reported as occurring in the city water mains at Lawrence, Kansas.[3]

These two examples probably illustrate how the manganese accumulated, and it is quite probable that manganese deposits similar to the Raymond occurrence will be found in other places in the Dakota area. A locality has been reported in Meade county on the Tertiary area where manganese has been precipitated as a coating on grains of quartz sands.[4] Professor E. Haworth also states that sands so coated are not uncommon in the Tertiary sands of the western part of Kansas.[5] It is quite unlikely that any such will have commercial importance.

[3] C. C. Young, *Proc. Ill. Water Supply Ass'n*, 1913, p. 81.
[4] C. C. Young, Master's Thesis, University of Kansas.
[5] E. Haworth, personal communication.

DISCUSSION

This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.

THE ORIGIN OF CHRYSOTILE VEINS.

Sir:—The memoir by Mr. R. P. D. Graham on the "Origin of Massive Serpentine and Chrysotile-Asbestos, Black Lake-Thetford Area, Quebec," in ECONOMIC GEOLOGY, Vol. XII., No. 2, is of especial interest to me as I have recently been making a detailed investigation of the origin of veins of the fibrous minerals. Mr. Graham's paper contains data of much value regarding the geological relations, occurrence, origin and physical properties of chrysotile. The exposures furnished by the Canadian chrysotile mines offer unequalled opportunities for the study of serpentinization with its accompanying volumetric changes, as well as the formation of chrysotile; and therefore, it is to be regretted that more analyses of the rocks and rock-forming minerals associated with the chrysotile deposits are not available. It is my purpose here, however, to discuss only that portion of Mr. Graham's memoir relating to the origin of the chrysotile veins.

Lats year I published a paper[1] giving my conclusions concerning the origin of veins of the asbestiform minerals. These conclusions were, in part, based on results obtained from certain experiments in the laboratory production of fibrous crystals. The paper was afterwards discussed[2] by Mr. Graham and others,

[1] "The Genesis of Asbestos and Asbestiform Minerals," *Bull. Amer. Inst. Min. Eng.*, No. 119, pp. 1973–1998, November, 1916.

[2] *Bull. Amer. Inst. Min. Eng.*, No. 123, pp. 397–405, March, 1917, and No. 125, May, 1917.

but at that time he did not outline his own theories. I welcomed Mr. Graham's discussion of my paper, since it is largely through frank criticism of one another's theories that errors are eliminated and the truth established. We seem to be substantially in accord as to the observed facts, but differ somewhat in our interpretation of them.

Mr. Graham adopts and expands the theory advanced by Dresser[3] that the veins are portions of the serpentine wall rock which have recrystallized *in situ*. My theory, which is not limited to chrysotile veins but is applicable to all cross-fiber veins, is briefly as follows: Cross-fiber veins have made room for themselves by pushing apart the walls with which they are in contact, and they owe their peculiar structure to the fact that the material for growth was supplied only at the base of the growing crystals through solutions occupying small, closely spaced openings in the walls. The fibrous structure is accentuated in asbestiform minerals by a normal prismatic habit and cleavage. The arguments in favor of the latter theory have been given in some detail elsewhere, so it is not necessary to repeat them here.

After confirming the observation of Dresser that there is a constant ratio between the width of a chrysotile vein and of the inclosing band of massive serpentine, Mr. Graham states: "The close interdependence in the volumes of the two varieties affords the most significant evidence yet offered that the one is a direct replacement of the other" (p. 184). But this ratio is exceptional, and does not hold for other serpentine rocks which are similar in chemical and mineral composition. Is it not as reasonable to assume that, under the conditions of temperature, pressure, etc., existing during serpentinization, a definite proportion of the mineral was taken into solution and redeposited in the form of veins?

Since massive serpentine and chrysotile have the same chemical composition, the same optical properties and the same specific gravity, there seems to be no reason for calling chyrsotile the

[3] Dresser, J. A., "Preliminary Report on the Serpentine and Associated Rocks of Southern Quebec," *Canada Department of Mines, Geological Survey, Memoir* No. 22, pp. 65-66, 1913.

"more perfect crystalline form of the mineral" (p. 191), or for attributing its origin to "complete serpentinization" (pp. 192–193). Why should the complete serpentinization of rocks always be limited to zones not more than 2 or 3 inches in width? And why should the "completely serpentinized zone" contain angular inclusion of massive serpentine situated, more often than not, near the central parting where the alteration is supposed to have begun? This is especially difficult to understand if there has been "repeated recrystallization" of the chrysotile (p. 197). The relatively greater freedom of chrysotile veins from mineral impurities is easily explained on the hypothesis that the growing crystals have largely excluded and pushed back the other minerals contained in the wall rock.

"Both the parallelism of the fibers and their transverse attitude," Mr. Graham states, "are structural features which are indicative of an expansive, rather than a compressive, strain" (p. 195), and he advances the hypothesis that the direction of elongation of the fibers in chrysotile veins is due to crystallization under differential pressure. According to this view, "the peridotite batholith was a cooling mass at the time it was undergoing alteration to serpentine," and there was, therefore, a tendency for the vein fissure to open because of the "contraction due to cooling" (pp. 195–198). This hypothesis is accompanied by the corollary "that chrysotile veins would never be found in cases where there was no contraction of the rock masses to counteract the expansion incident to serpentinization" (p. 198). With this view I can not agree, since crystal fibers may be elongated in the direction of greatest pressure providing they are in contact with supersaturated solutions only in that direction. This fact has now been proved experimentally for substances which separate from solution with contraction in total volume, as well as for those that separate with expansion in total volume.[4]

Moreover the hypothesis is in conflict with much observational evidence. Where chrysotile veins have been formed through the serpentinization of igneous rocks, the distribution of the

[4] Taber, Stephen, "Pressure Phenomena Accompanying the Growth of Crystals," *Proc. Nat. Acad. Sci.*, Vol. 3, pp. 299–300, April, 1917.

veins with reference to the cooling surfaces is not such as would be expected if they were due to contraction on cooling; and open fissures due to shrinkage are not characteristic of peridotite, such as those of the South Atlantic States, which have been only slightly altered to serpentine. The lenticular shape of many of the veins likewise argues against this theory, as does also the presence of chrysotile veins in serpentine that has been formed through the alteration of masses of pyroxene in crystalline limestones.

In conclusion attention is called to the fact that the structural peculiarities characteristic of chrysotile veins are likewise to be found in the cross-fiber veins of other minerals, such as gypsum, calcite and especially crocidolite, all of which are found in sedimentary rocks. An adequate theory of the formation of cross-fiber veins must take this into consideration, and also the fact that the veins and wall rock are not always similar in mineral composition. An adequate theory must account for the presence of one or more partings in some veins and their absence in others; it must satisfactorily explain the irregular nature of these partings; it must explain the presence of the angular fragments of wall rock that frequently mark the partings, and are also unevenly distributed through the veins; it must explain why the fibers are normal to the walls in some instances and oblique in others; it must explain the presence of sharp bends and gentle curves in the parallel fibers; it must account for the fact that all minerals having fibrous varieties are also found in non-fibrous forms.

STEPHEN TABER.

REVIEWS

Oil Field Development and Petroleum Mining. By A. BEEBY THOMPSON. 626 pp., with eight colored maps, 152 plates and text figures. New York, D. Van Nostrand Co. Price $7.50.

With the great expansion of the petroleum industry in the past decade has come a call for geologic advice so insistent that a considerable number of well-trained geologists are now devoting their entire attention to the problems involved in the location and exploitation of the world's petroleum resources. The resulting increased scientific interest in the subject has found expression in numerous valuable short articles in the periodical press, but the conspicuous lack of comprehensive standard treatises has been keenly felt by petroleum geologists. Höfer's "Das Erdöl," inaccessible to many American geologists, needs revision in the light of recent work; Redwood's "Petroleum" is an invaluable catalogue of the industry, but it does not treat adequately of petroleum geology and is moreover a notorious example of the scrapbook method of writing. In the last half of 1916, however, petroleum literature was enriched by three books: Johnson and Huntley's "Oil and Gas Production," a suggestive and instructive work, but hastily written and rather poorly arranged; Bacon and Hamor's "American Petroleum Industry," in large part a compilation or reprint of material published elsewhere, but a valuable and comprehensive handbook of the petroleum industry, replete with references; and Thompson's "Oil Field Development," a stimulating and readable work on petroleum geology and technology, especially valuable to American geologists because of its authoritative description of foreign fields and methods.

A complete treatise on petroleum should describe the geologic occurrence and relations of petroleum, its chemical character, and the probable factors involved in its origin and migration; methods of drilling wells, producing petroleum and handling oil field properties; methods of refining petroleum and the products obtained; the location and the salient geologic and technologic features of the principal oil fields of the world. It is impossible adequately to treat all of these phases within the limits of a single volume, and Mr. Thompson has wisely refrained from attempting to do so and has discussed chiefly geology and oil field development. Few geologists or oil operators will regret that the sec-

tion on refining is merely a short lucid description of the general principles. The omission of a geologic description of the world's petroleum fields is more serious, but it is partly remedied by a short general account and by numerous references throughout the book to geologic conditions in specific fields.

In view of the technologic character of the book's title, geologists may be surprised to learn that the work contains a comprehensive and modern discussion of the principles of petroleum geology, the most satisfactory in the reviewer's opinion that has yet appeared. Theories of the origin and migration of petroleum are accorded adequate treatment, but the book is in no sense academic; it is very evident that the author is a keen first-hand observer and that his experience has been exceptionally broad. The author's fifteen years of service as a petroleum geologist and engineer has been spent almost entirely in foreign fields, and though American geologists may regret that his knowledge of fields in the United States is derived chiefly from the literature, they will value the more his accounts of conditions abroad. For a similar reason the technologic portion of the work also will be particularly instructive to American operators; the description of American drilling methods, for example, is no better than may be found in several other works, but the correlation of these methods with those practised in foreign fields, and the appraisement of the relative value of different drilling systems under different geologic conditions by an engineer well qualified to judge is a feature that should be welcomed.

The work consists of four parts: (1) a 50-page account of the geographic distribution of petroleum; (2) about 200 pages on the geology and chemistry of petroleum; (3) a section on oil field development comprising 280 pages; (4) several short chapters on the economic and financial aspects of the oil business.

The opening chapter, on the geographic distribution of petroleum, is a brief account of the development, production, and commercial relations of the principal fields of the world. It is in general a good summary but too short to be of value for reference except in the broadest way, especially as citations to more detailed literature are practically lacking. The space allotted to American fields is disproportionately small in view of their commercial importance and geologic interest, and several minor errors were noted. The eight colored maps designed to accompany this chapter are not particularly pleasing.

Chapter 2 deals with the commercial aspects of petroleum, local customs regarding leasing and fixing royalties in various parts of the world, and the valuation of oil properties. This chapter seems out of place; the first part might better have been placed in chapter 1 and the remainder relegated to the end of the book where various phases of

accounting and management are discussed in detail. The section on local customs is, however, one of the most novel and pleasing features of the work. The section on valuation is fair, but does not adequately treat of the latest and best American practice.

Chapters 3, 4 and 5 deal with petroleum geology. Chapter 3, on factors governing the formation, migration, and accumulation of petroleum, the character of oil field strata, and the production and life of oil fields, is one of the best in the book. It is embellished by a number of photomicrographs showing the character of typical oil sands, and contains charts showing the life history of representative oil wells and fields. The sections on movements of petroleum occasioned by development and on the area influenced by producing wells are especially valuable. Chapter 4 is an excellent description of surface indications of petroleum and phenomena associated with its occurrence. However, the inclusion under this head of a short section on oil shales (in which, by the way, American oil shales are not mentioned) is certainly open to criticism. Chapter 5 deals with oil field structures and is illustrated by a number of three-dimension sections, which may prove more attractive to the student than structure contour maps. The author's classification of oil field structures seems rather artificial and is less desirable than F. G. Clapp's, but his illustrations of the several types are generally well chosen. Moreover, it is a pleasure to record that structure is treated not as the sole and all-embracing consideration of petroleum geology, but merely as an important phase of the same.

Chapter 6 deals with the origin, composition, properties and treatment of petroleum. Theories of inorganic origin are reduced to a minimum; theories of organic origin are discussed at length and special emphasis is laid on the influence of bacteria. The second half of the chapter, on chemical composition and methods of treatment, is a good synopsis.

Chapter 7 is devoted to methods of drilling, the cable, pole tool, hydraulic, core drill and rotary systems being described in detail and their relative values pointed out. Numerous illustrations of the various tools used are given, and also specifications for building standard cable, pole tool and rotary rigs. The importance of keeping adequate well logs is also briefly discussed. Casing and the appliances used in its insertion, manipulation, extraction and repair are discussed in chapter 8, and methods of excluding water from the wells in chapter 9. Probably few men have had a wider experience with different drilling systems than the author and few are better qualified to write a well-balanced description of drilling practice the world over.

Chapter 10 deals with the extraction of petroleum and gas. The control of flowing wells, and production by means of pumping, bailing,

swabbing, and the air lift are described. The author's long experience in the Russian fields has led him to describe the bailing system in detail and his account should prove of interest to American operators. Chapter 11 treats of oil field equipment, including the selection of power, the design and construction of pipe lines, and the measurement and storage of oil. Chapter 12 is an excellent brief description of natural gas, its composition, production, measurement and transportation. The condensation of gasoline from gas is also described. Chapter 13 is devoted to the compilation of statistical records and contains several useful forms and specimen charts. Chapter 14 discusses the organization of oil companies and the principles of accounting and management.

In discussing oil field phenomena and development methods the author has drawn freely on his own store of personal observations, and at the same time has not neglected the observations and reflections of other workers, as recorded in the literature. His work is marred, however, by the fact that citations to the literature are not abundant and that many of those given are inadequately worded or inaccurate. It is not a question of not according credit, but simply of decreasing the usefulness of the book to the student who desires to pursue farther some particular phase of the subject. On page 114, for example, reference is made in the text to some very interesting observations by Charles Moore, on the porosity of sandstone in the vicinity of faults, but the reader is uninformed as to whether the information is derived from a personal communication from Mr. Moore or from a published report describing his observations in detail.

On page 116, accompanying an apparent quotation from Messrs. Hayes and Kennedy—which by the way is not a quotation but an abstract or paraphrase—is the footnote "Report, Geological Survey, United States, 1903." As the United States Geological Survey published fifty or more reports in 1903 it is not obvious that the citation is to U. S. Geological Survey Bull. 212, entitled Oil fields of the Texas-Louisiana Gulf Coastal Plain. On page 150 reference to the same report appears in more adequate form, but the number of the bulletin is given as 213; and on page 180 the same luckless publication is referred to as "United States Geological Survey, Report on Texas oil fields in 1903, by Hayes and Kennedy." In endeavoring to run down references given in this manner a minute familiarity with petroleum literature is evidently at a premium.

On page 143 reference to a paper on the decline of oil wells by L. G. Huntley, is given "Technical Paper 51, Petroleum Technology 11, L. G. Huntley, Bureau of Mines, Washington," and on page 145 the same paper is referred to as "The decline of oil wells, L. G. Huntley, Bureau of Mines, Washington, 1913." In the footnotes several errors that are

apparently typographical were also noted, such as 1914 instead of 1904 (page 160), and 809 instead of 309 (page 186), but the text seems to be practically free from such errors.

The book is not over long and the author is to be congratulated on having omitted bulky statistical tables that are of more or less transient value and are readily accessible elsewhere. "Principles rather than lengthy descriptions have been kept in view." One might question the desirability of repeating with slight changes on pages 6, 46 and 55, a short paragraph on the small oil strike at Calgary in 1914, and the local excitement attending it, but in general there is little repetition throughout the volume.

Because of the paucity of references to the literature the work can not be considered a handbook; it is rather a monograph on the geologic and engineering phases of the petroleum industry, carefully prepared by a well-trained observer of long practical experience. Although the book would be improved by a fuller treatment of the "hard rock" Appalachian and other Paleozoic fields as distinguished from the Tertiary deposits, it is in the main well balanced. It is a very readable work, well illustrated and attractively printed, and should prove an excellent textbook. It may be recommended to petroleum geologists, engineers, and operators as the best work of its kind.

G. SHERBURNE ROGERS.

SCIENTIFIC NOTES AND NEWS[1]

GLENN S. SMITH and ALFRED H. BROOKS, formerly of the U. S. Geological Survey, have received commissions as majors and are on active service in France. Mr. Smith is in charge of the topographic work of the American Engineer Corps, and Mr. Brooks is directing the geologic engineering.

H. V. WINCHELL, who has been in Russia and the Far East for the past few months, is due to return this month.

C. L. DAKE, of the Missouri School of Mines, has been doing field work for Valerius, McNutt and Hughes, of Tulsa, Okla.

H. N. WITT, of the Consolidated Gold Mines Co., has been spending the field season in British Columbia.

J. P. CHANNING has been visiting the Naumkeag exploration operations in the Michigan copper region.

E. S. BASTIN, of the U. S. Geological Survey, and A. P. Coleman, of the University of Toronto, are in South America.

SIDNEY H. BALL is in western Siberia.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.